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Lee et al.

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(54) **SEMICONDUCTOR DEVICE HAVING INTERCONNECTION STRUCTURE**

(71) Applicants: **Dohyun Lee**, Hwaseong-si (KR);
Youngwoo Park, Seoul (KR);
Junghoon Park, Yongin-si (KR);
Jaeduk Lee, Seongnam-si (KR)

(72) Inventors: **Dohyun Lee**, Hwaseong-si (KR);
Youngwoo Park, Seoul (KR);
Junghoon Park, Yongin-si (KR);
Jaeduk Lee, Seongnam-si (KR)

(73) Assignee: **Samsung Electronics Co., Ltd.**,
Gyeonggi-do (KR)

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Related U.S. Application Data

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H01L 21/768 (2006.01)

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(52) **U.S. Cl.**

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(Continued)

(58) **Field of Classification Search**

CPC H01L 21/76877; H01L 27/11575; H01L 27/11573; H01L 23/53266
See application file for complete search history.

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Primary Examiner — Laura M Menz

(74) *Attorney, Agent, or Firm* — Harness, Dickey & Pierce, P.L.C.

(57) **ABSTRACT**

A semiconductor device includes a semiconductor pattern on a semiconductor substrate, a three-dimensional memory array on the semiconductor pattern, and a peripheral interconnection structure between the semiconductor pattern and the semiconductor substrate. The peripheral interconnection structure includes an upper interconnection structure on a lower interconnection structure. The upper interconnection structure includes an upper interconnection and an upper barrier layer. The lower interconnection structure includes a lower interconnection and a lower barrier layer. The upper barrier layer is under a bottom surface of the upper interconnection and does not cover side surfaces of the upper interconnection. The lower barrier layer is under a bottom surface of the lower interconnection and covers side surfaces of the lower interconnection.

20 Claims, 38 Drawing Sheets

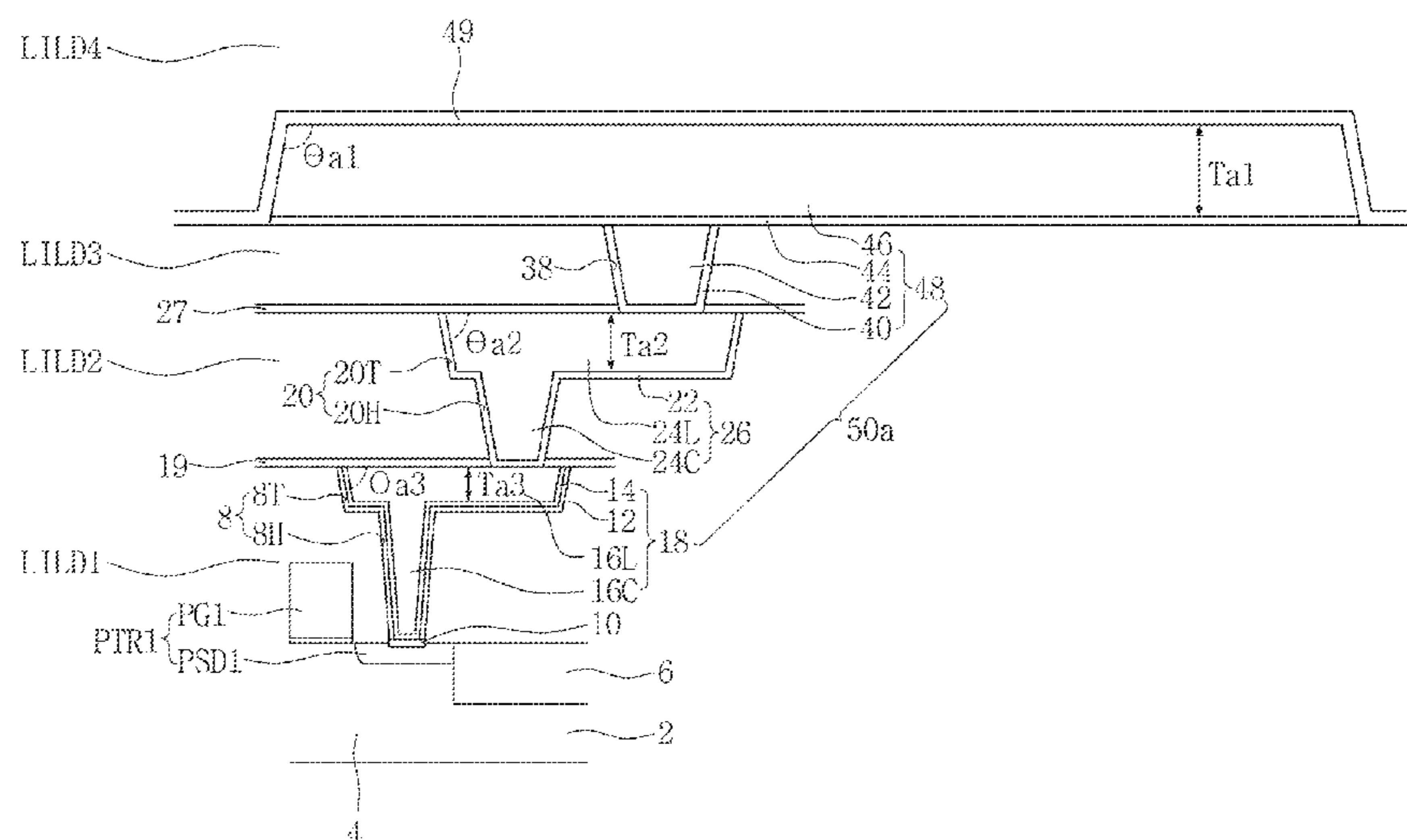


FIG. 2

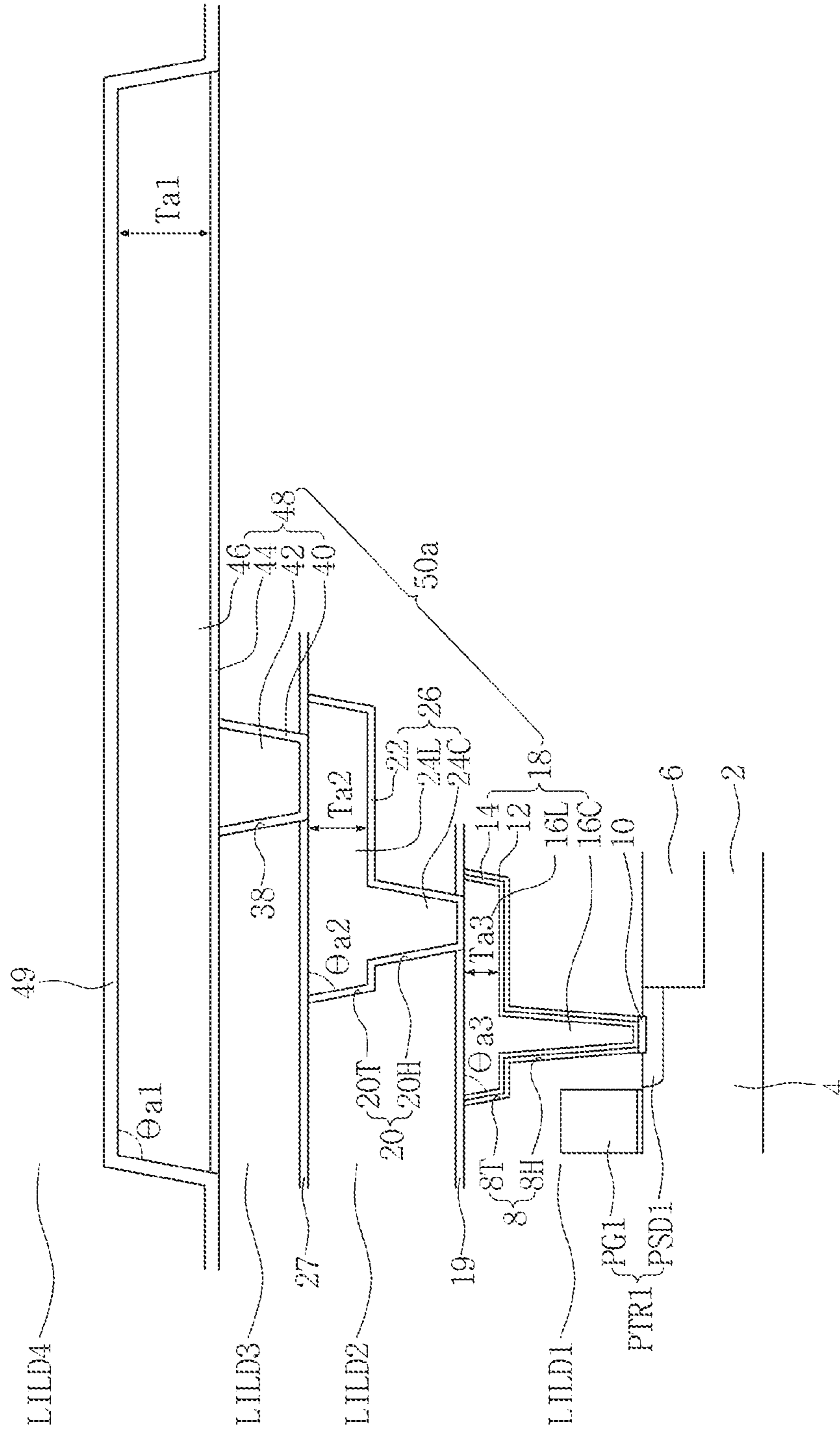


FIG. 3

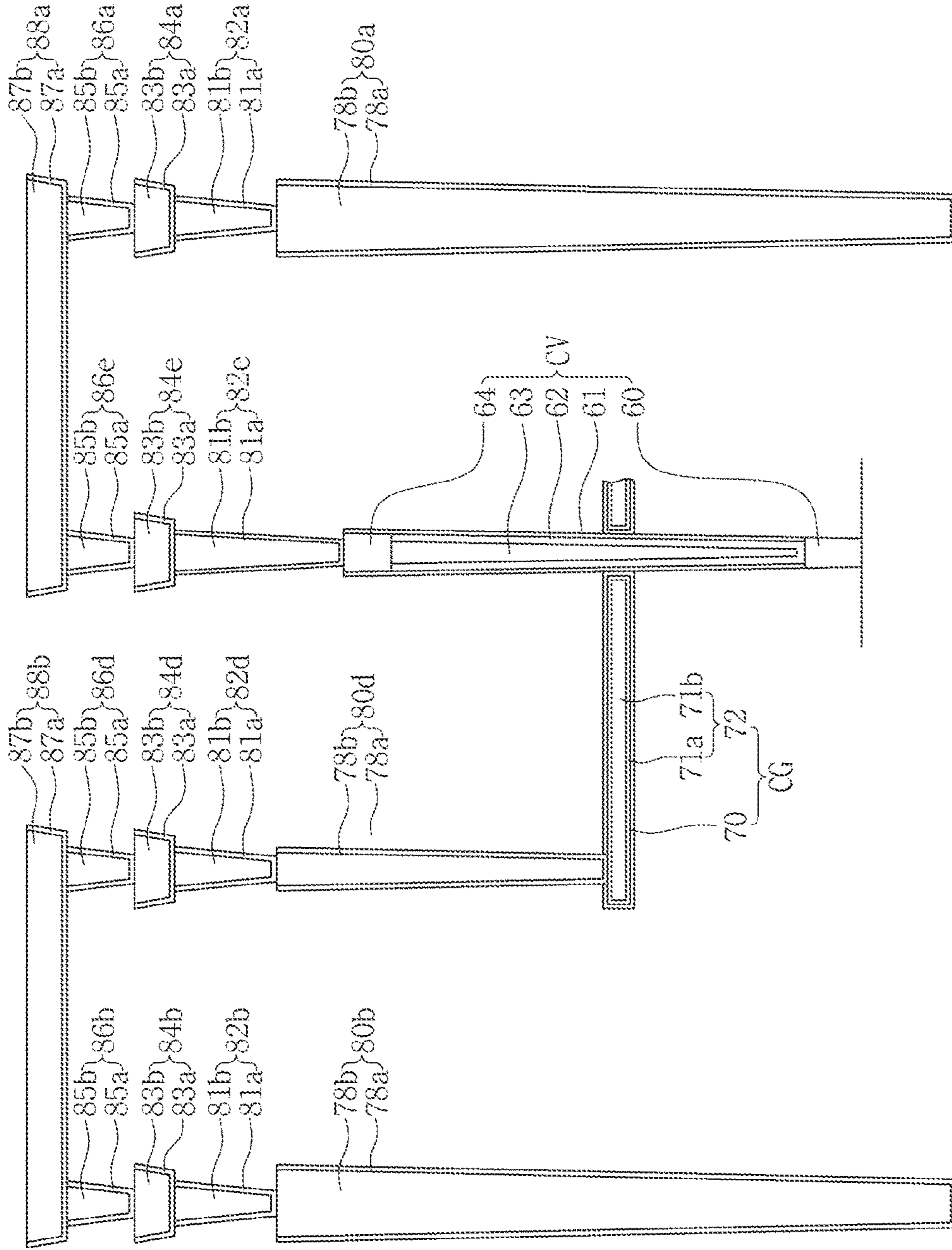


FIG. 5

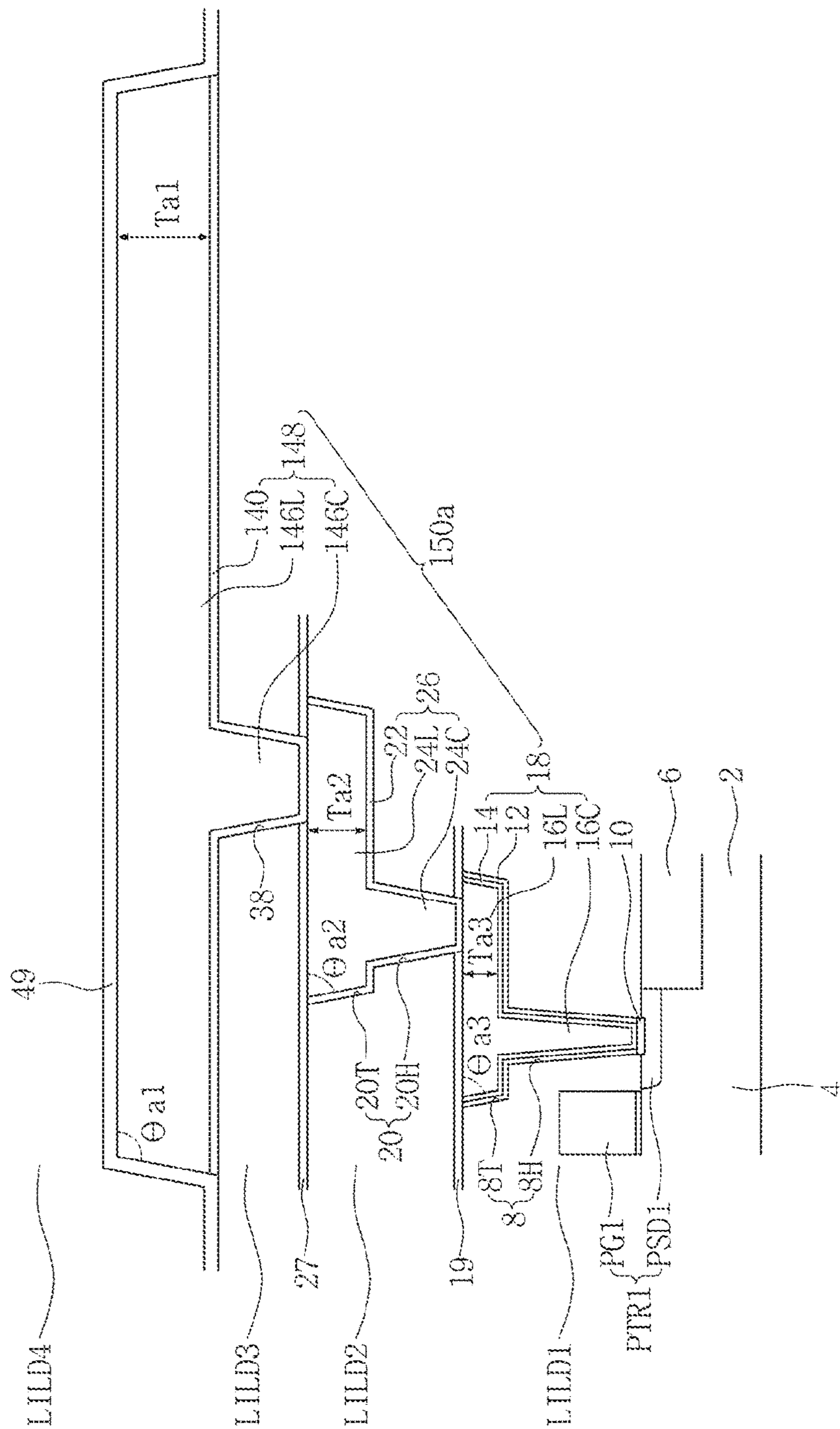


FIG. 6A

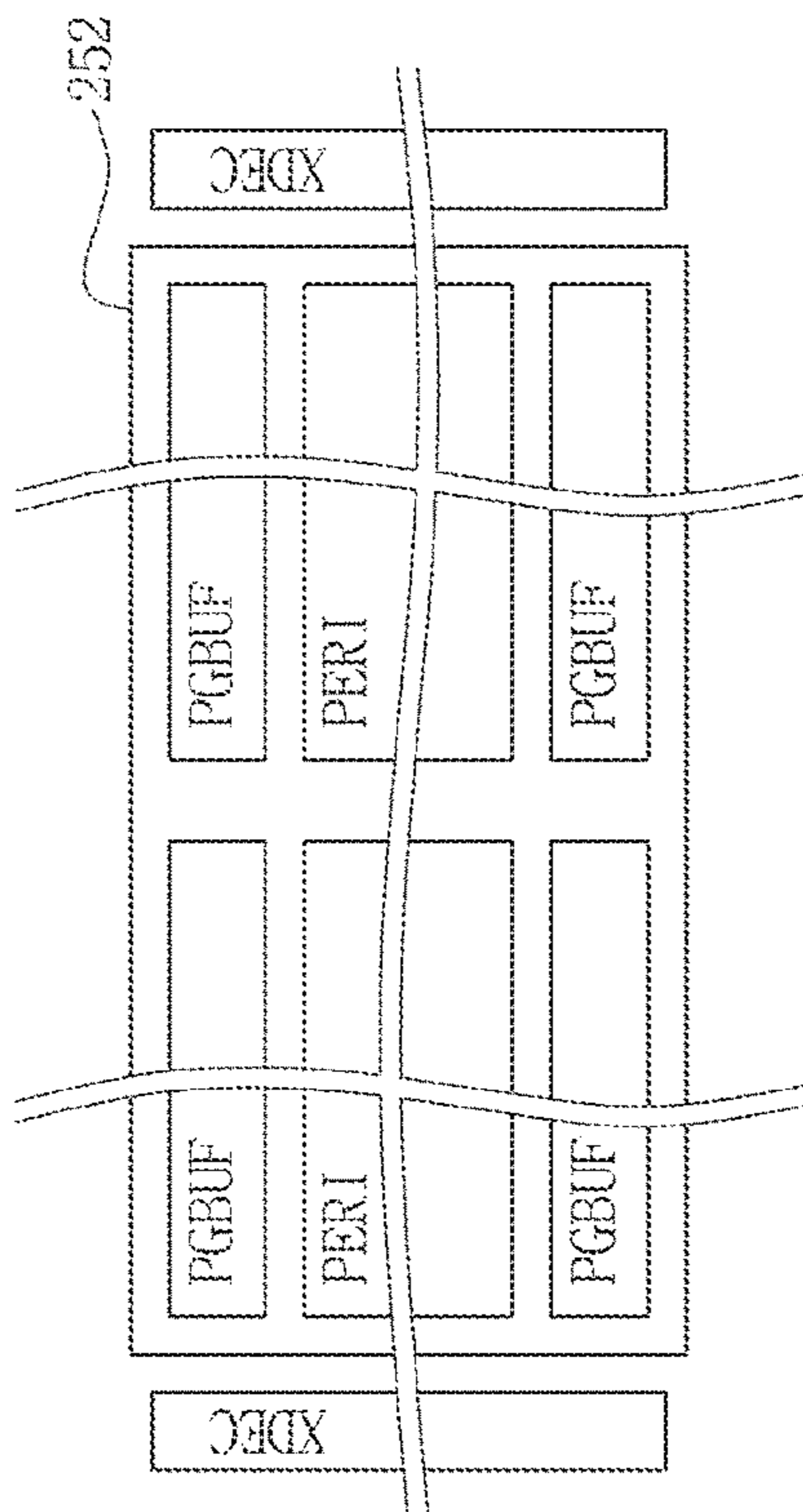


FIG. 6B

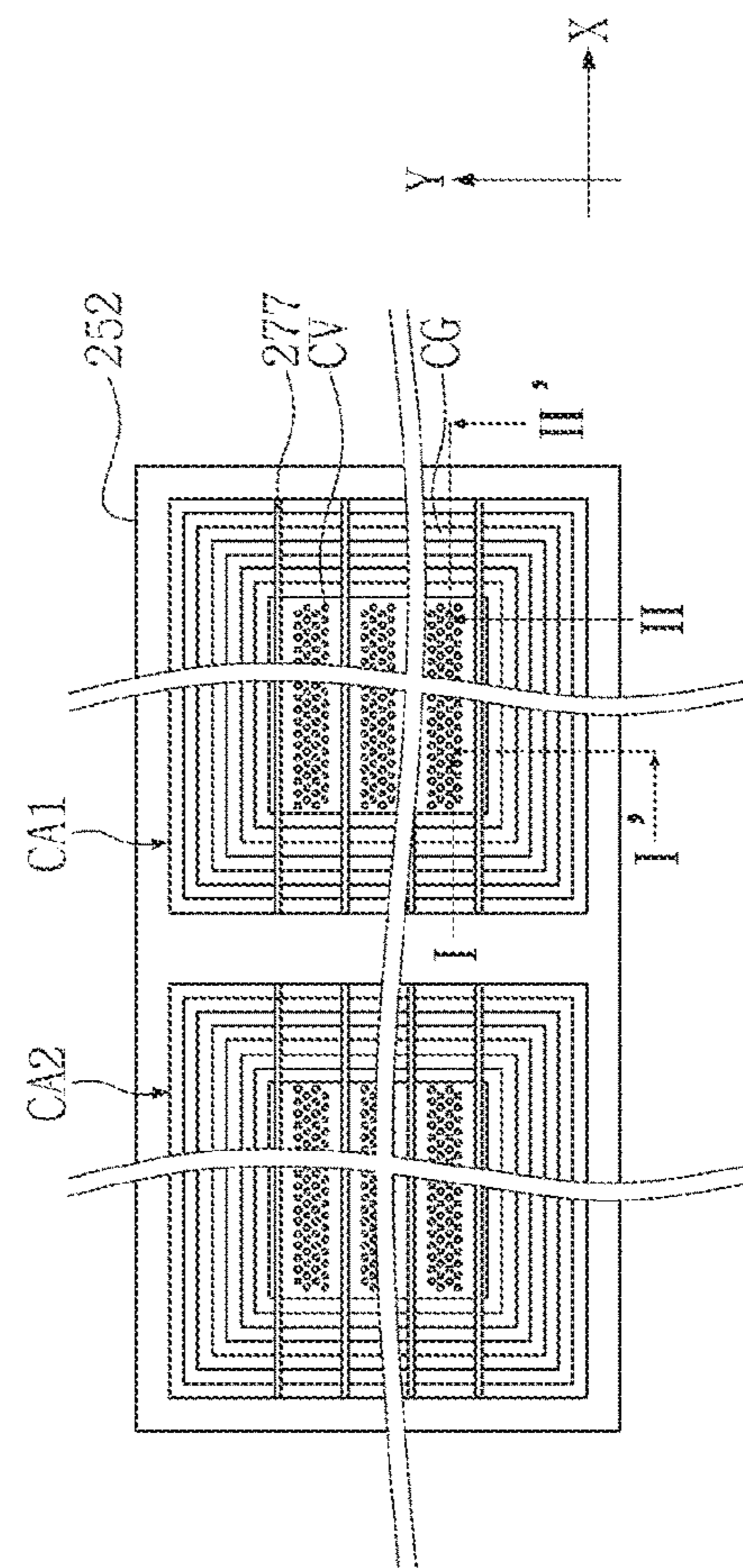


FIG. 9A

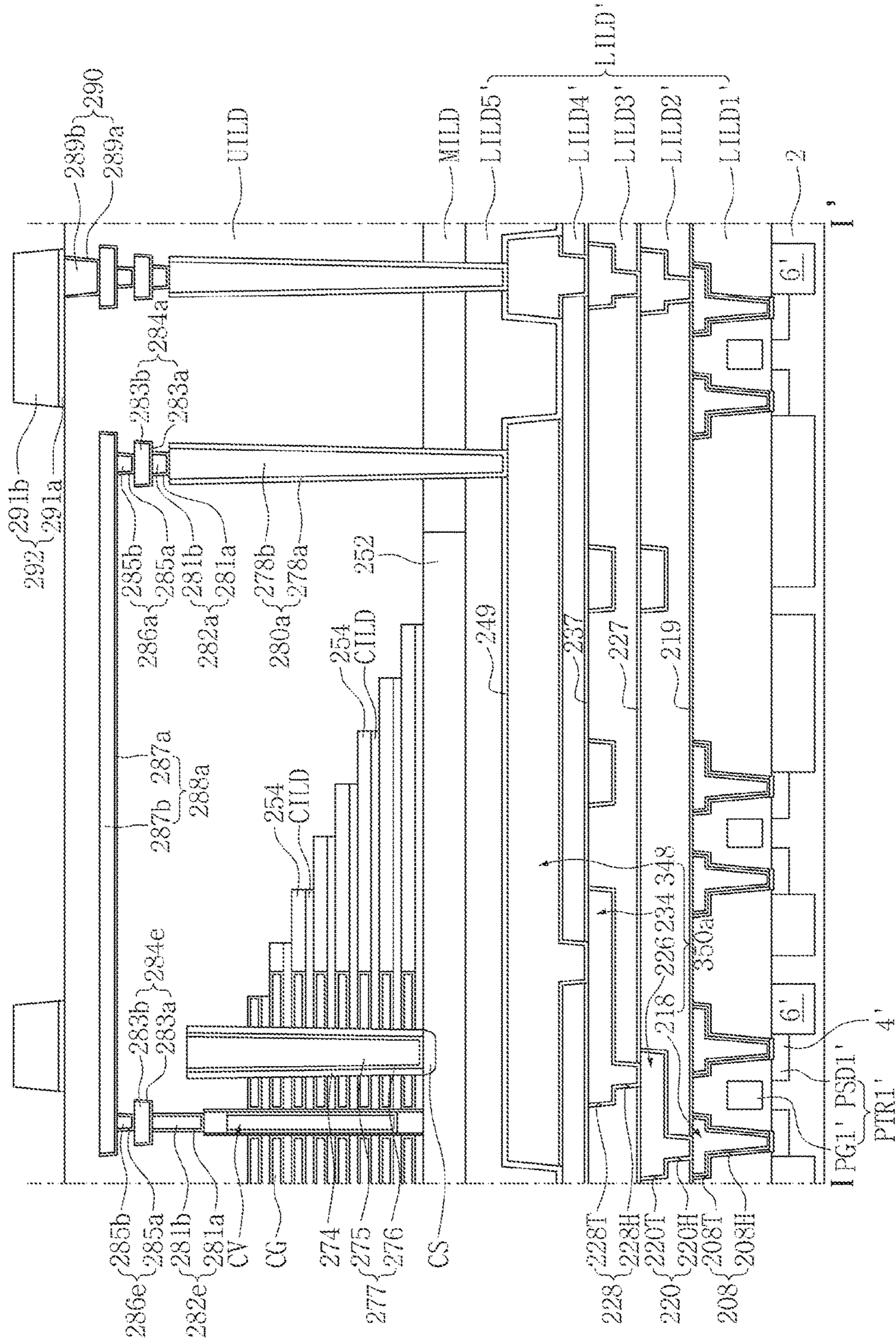


FIG. 9B

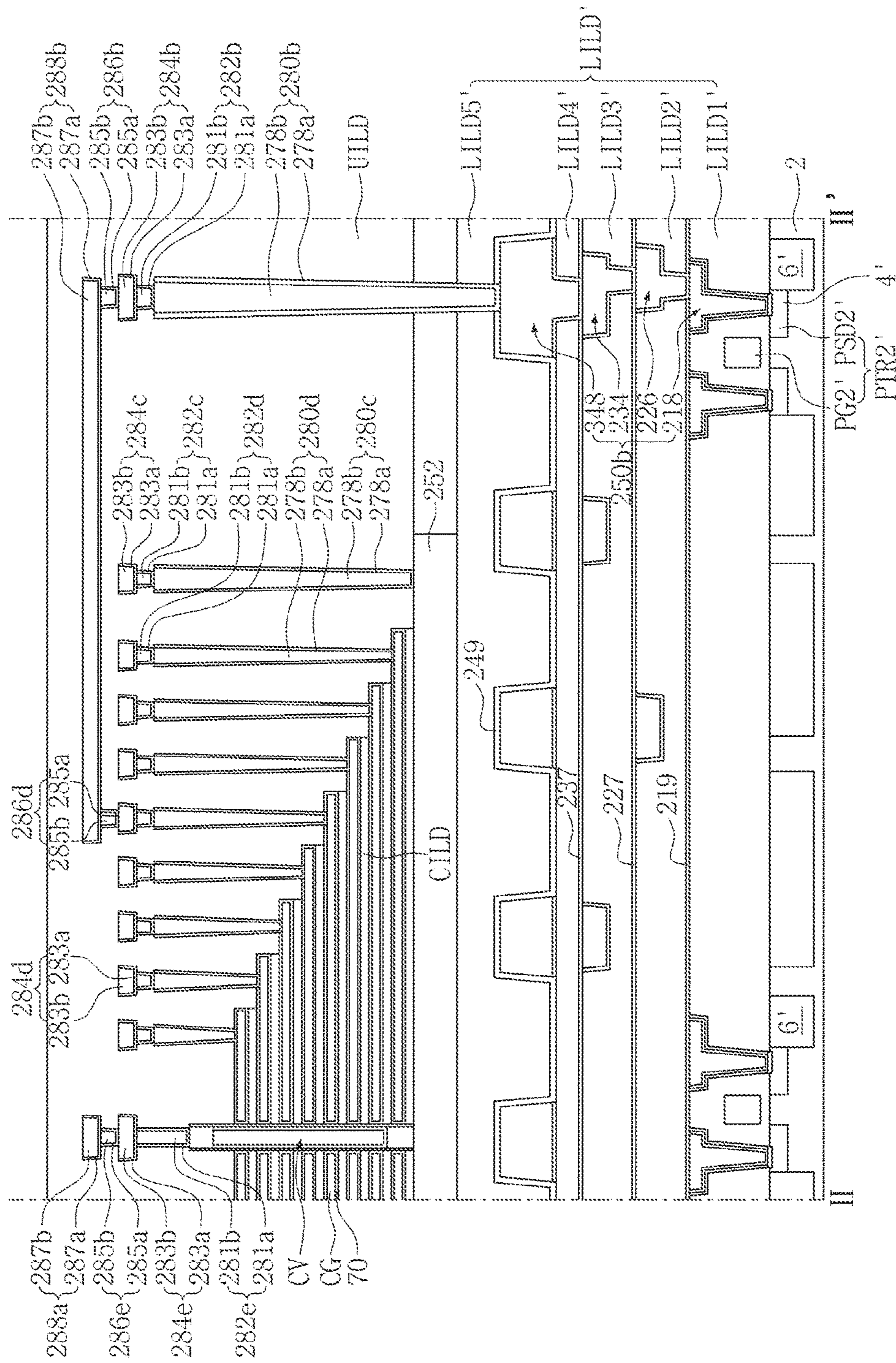


FIG. 10

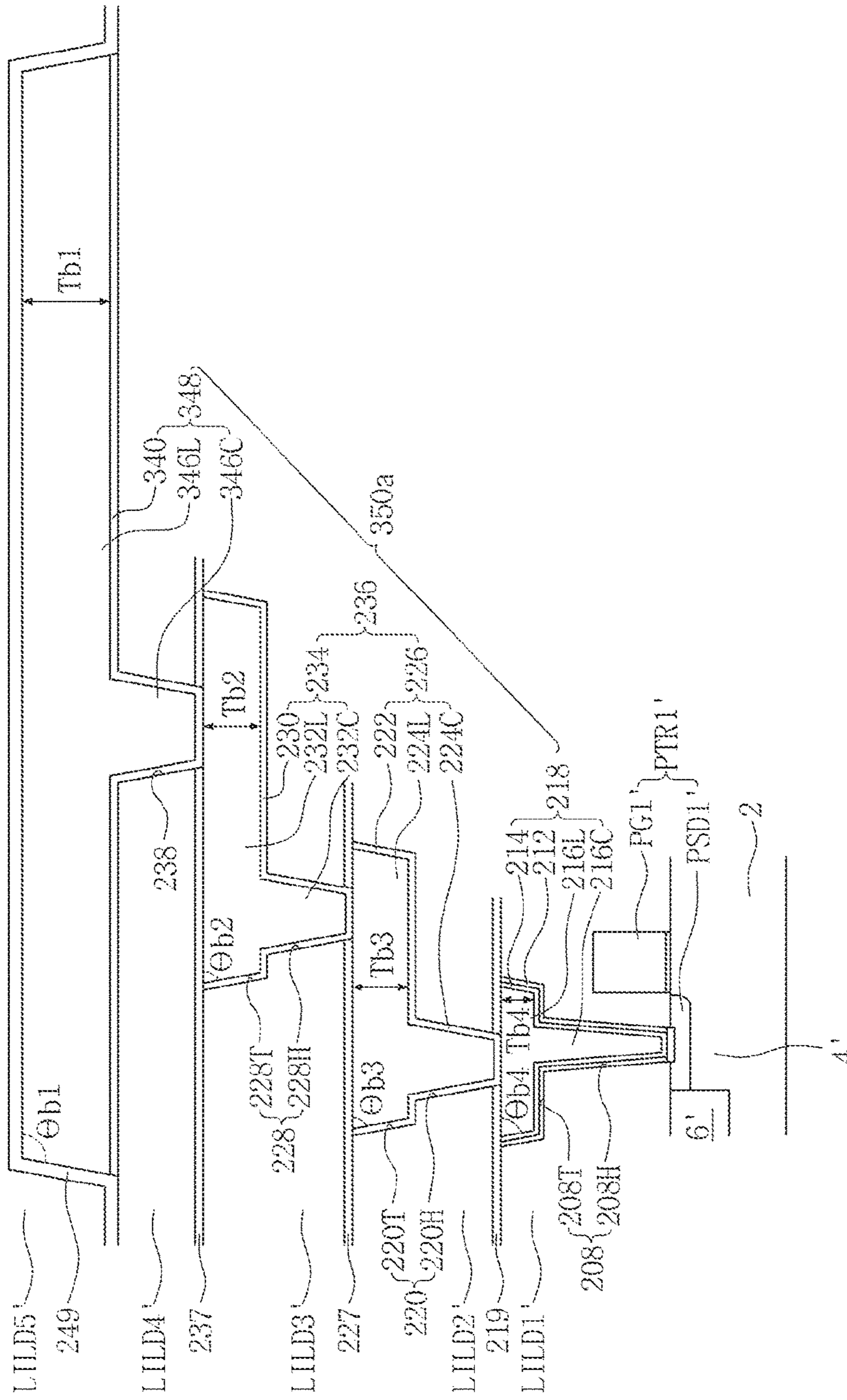


FIG. 11A

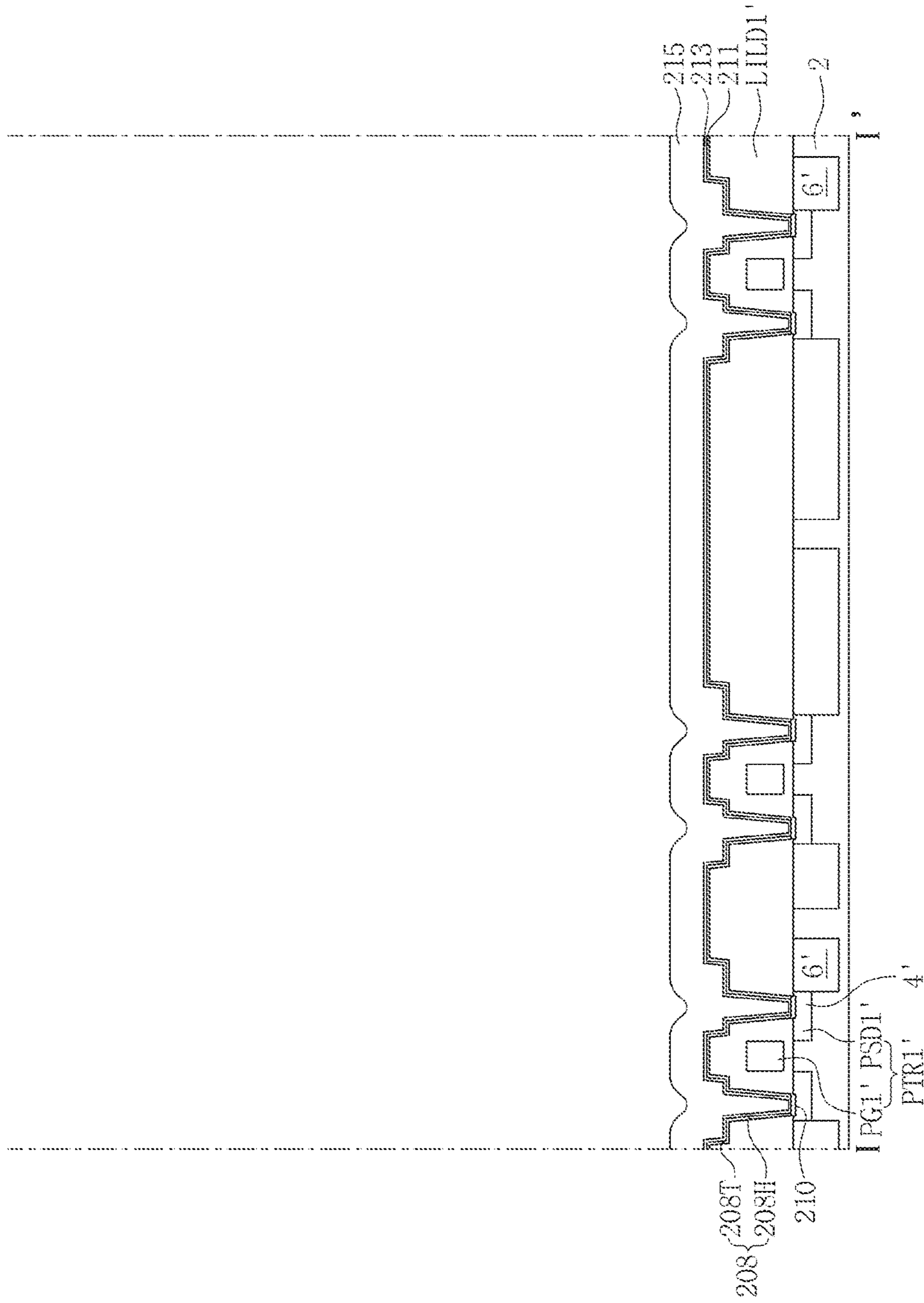


FIG. 11B

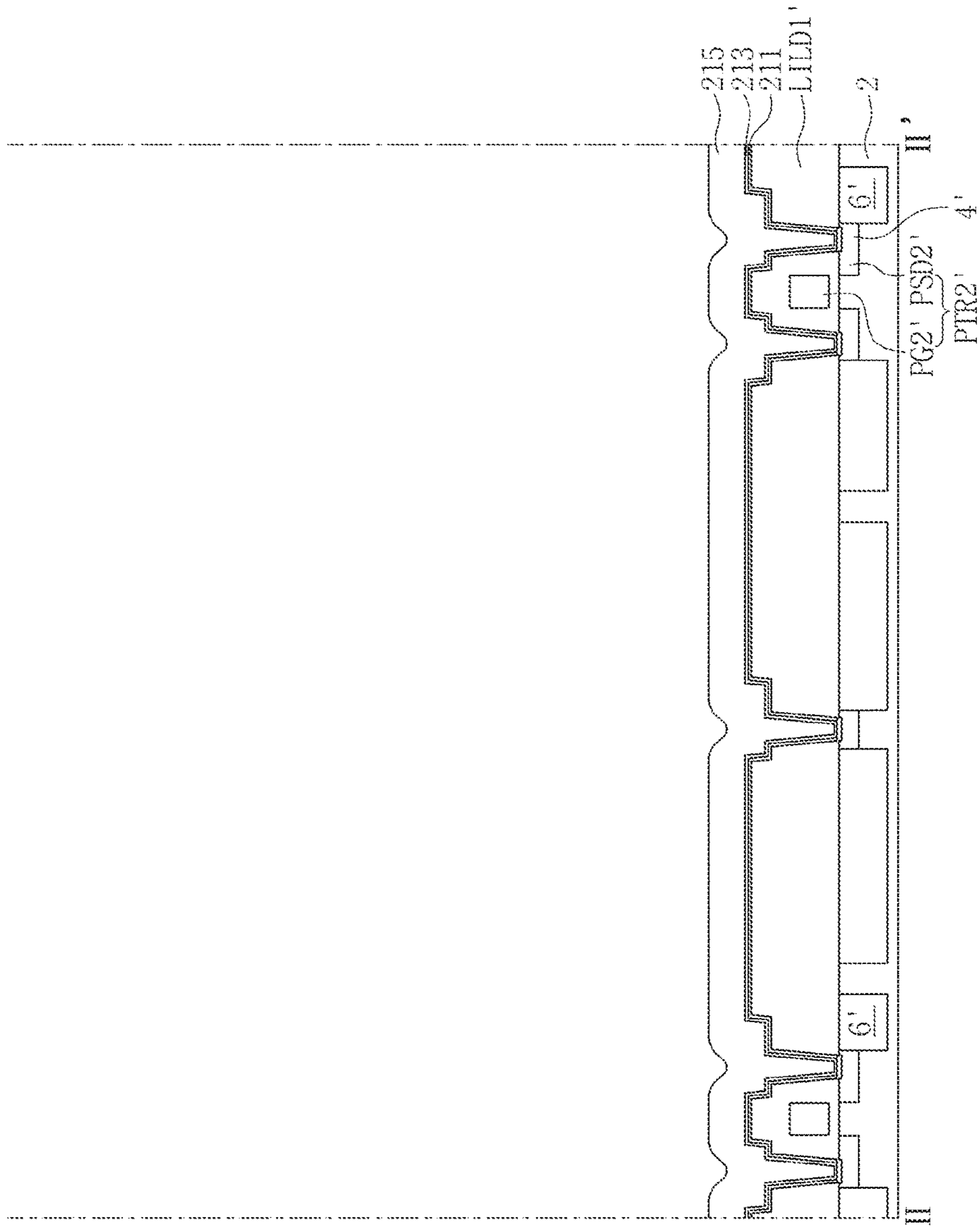


FIG. 12A

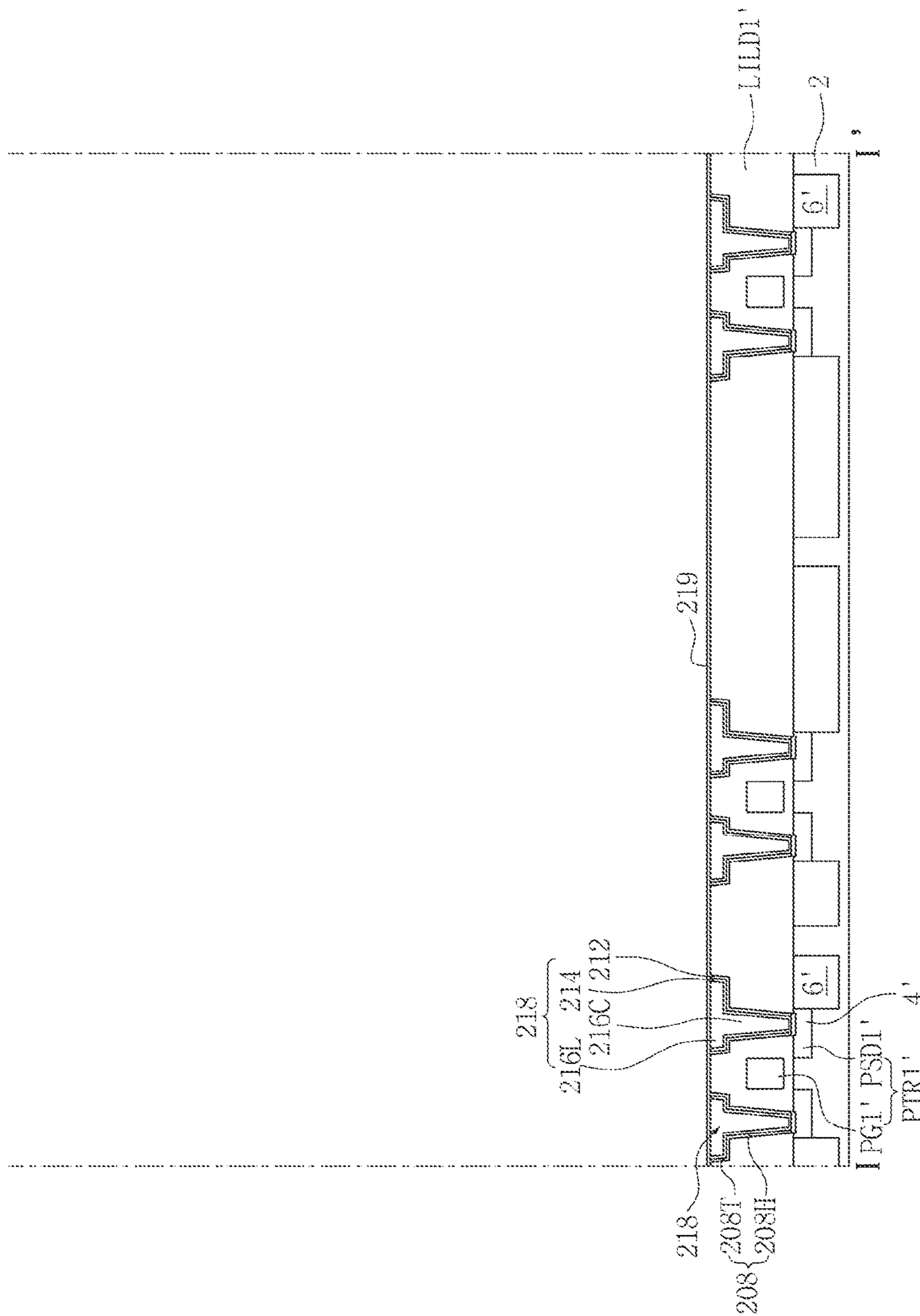


FIG. 12B

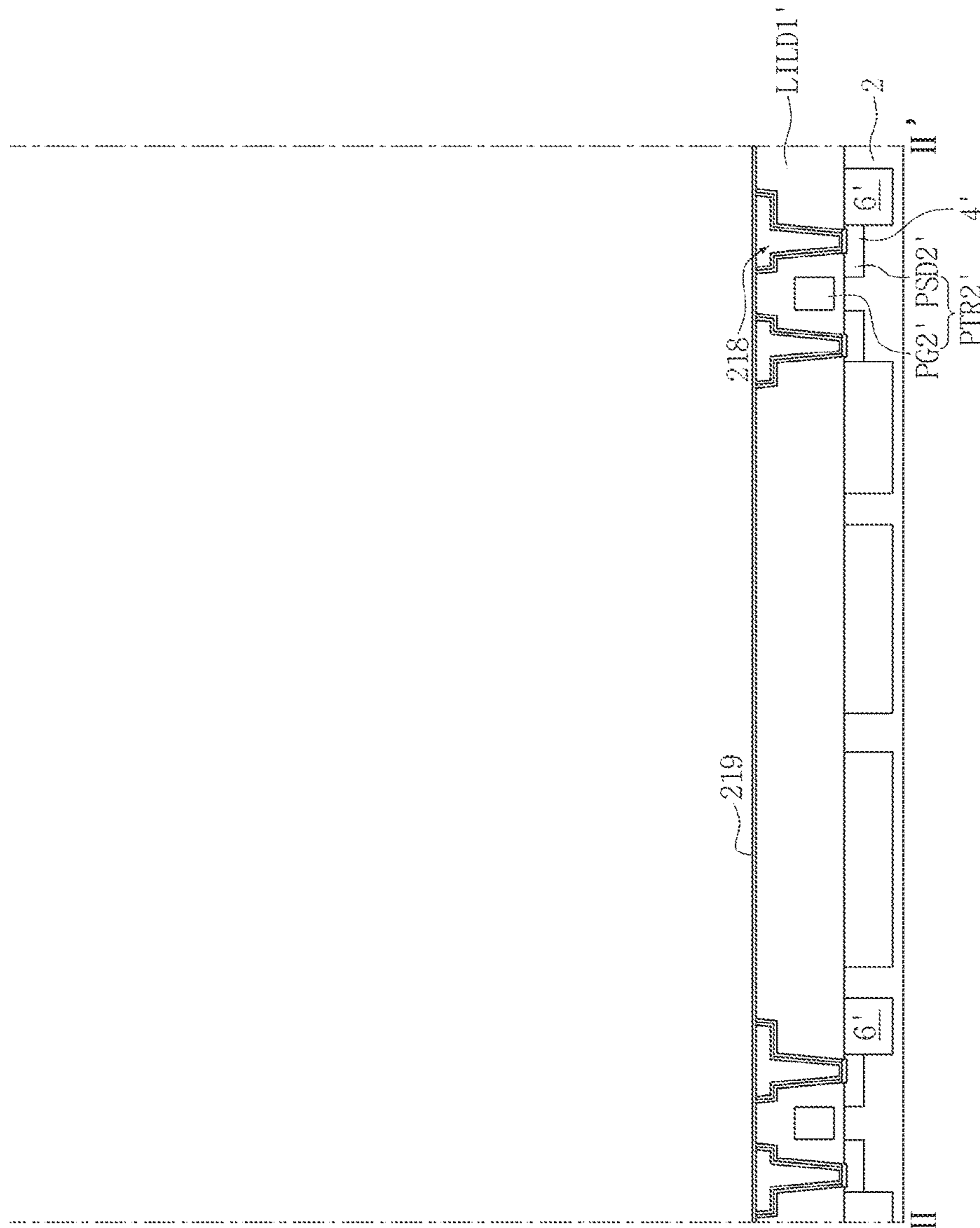


FIG. 13A



FIG. 13B

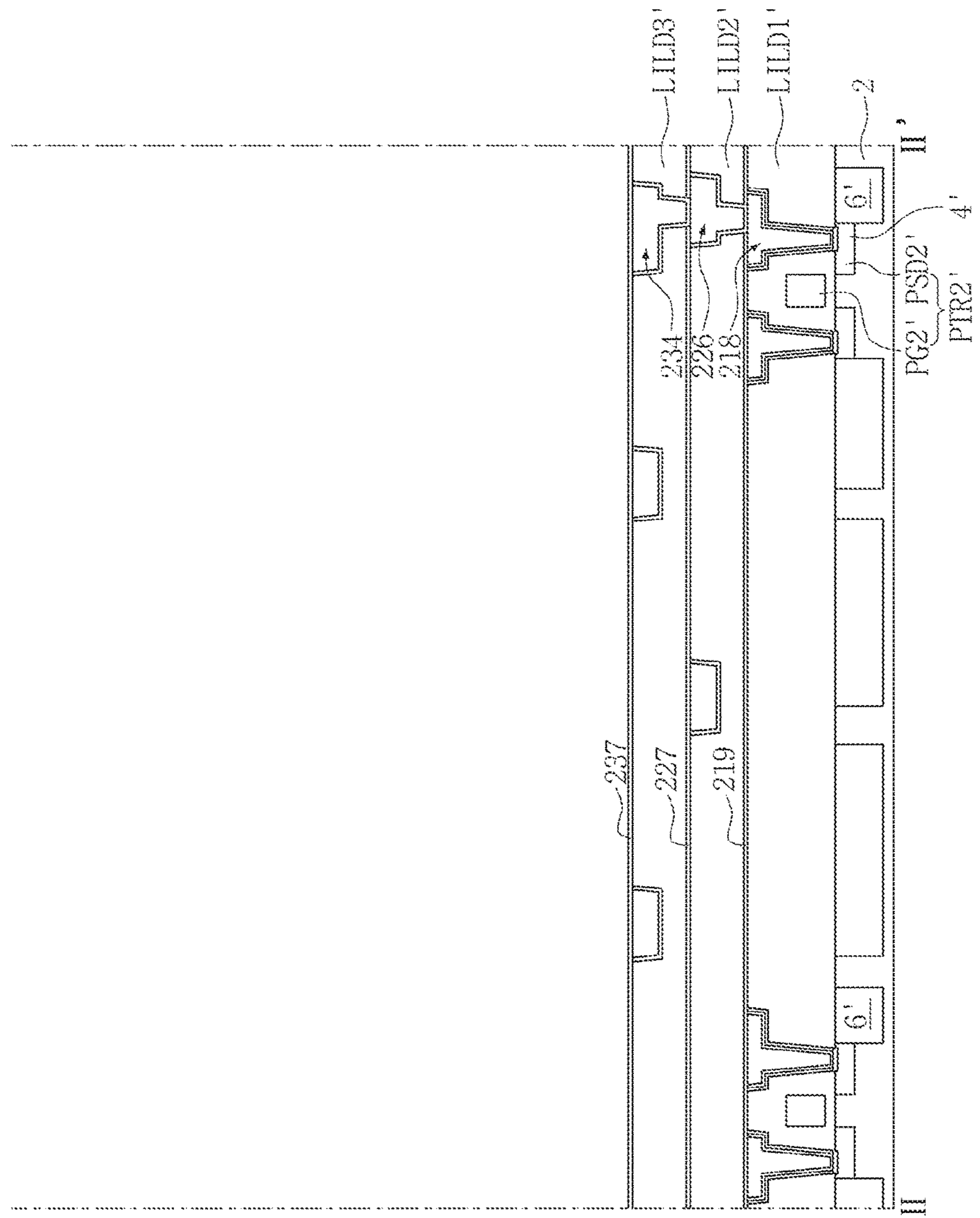


FIG. 14A

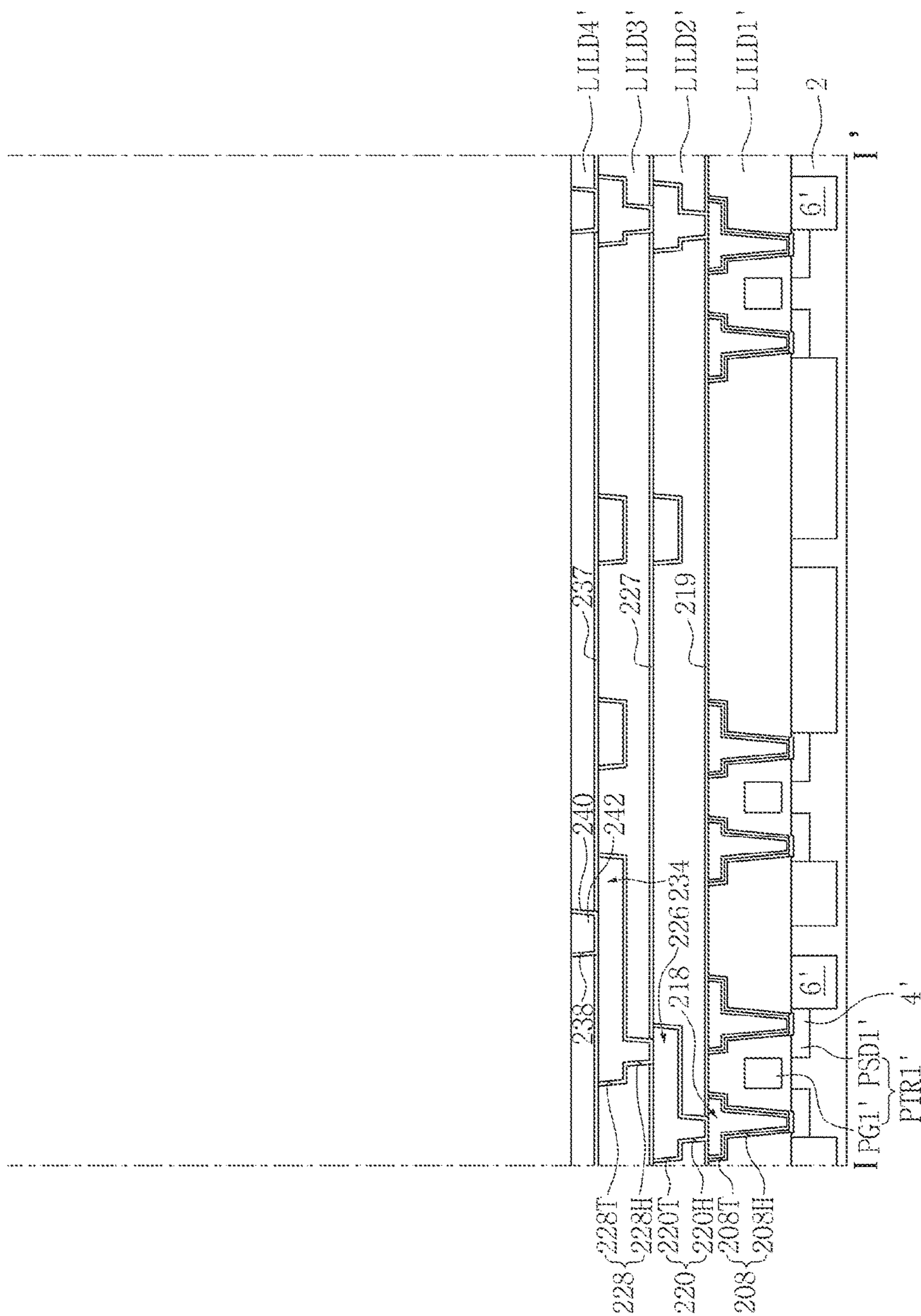


FIG. 14B

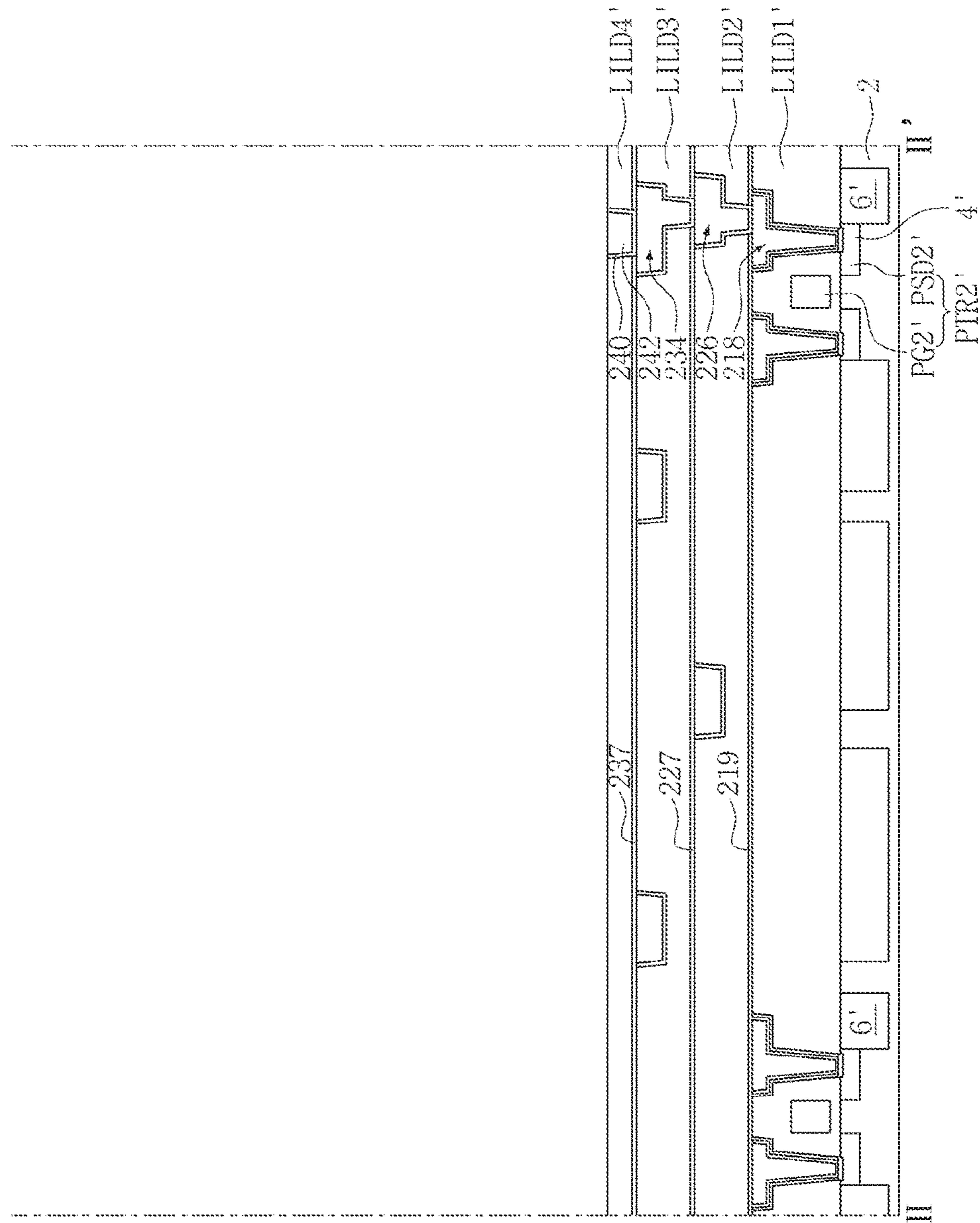


FIG. 15A

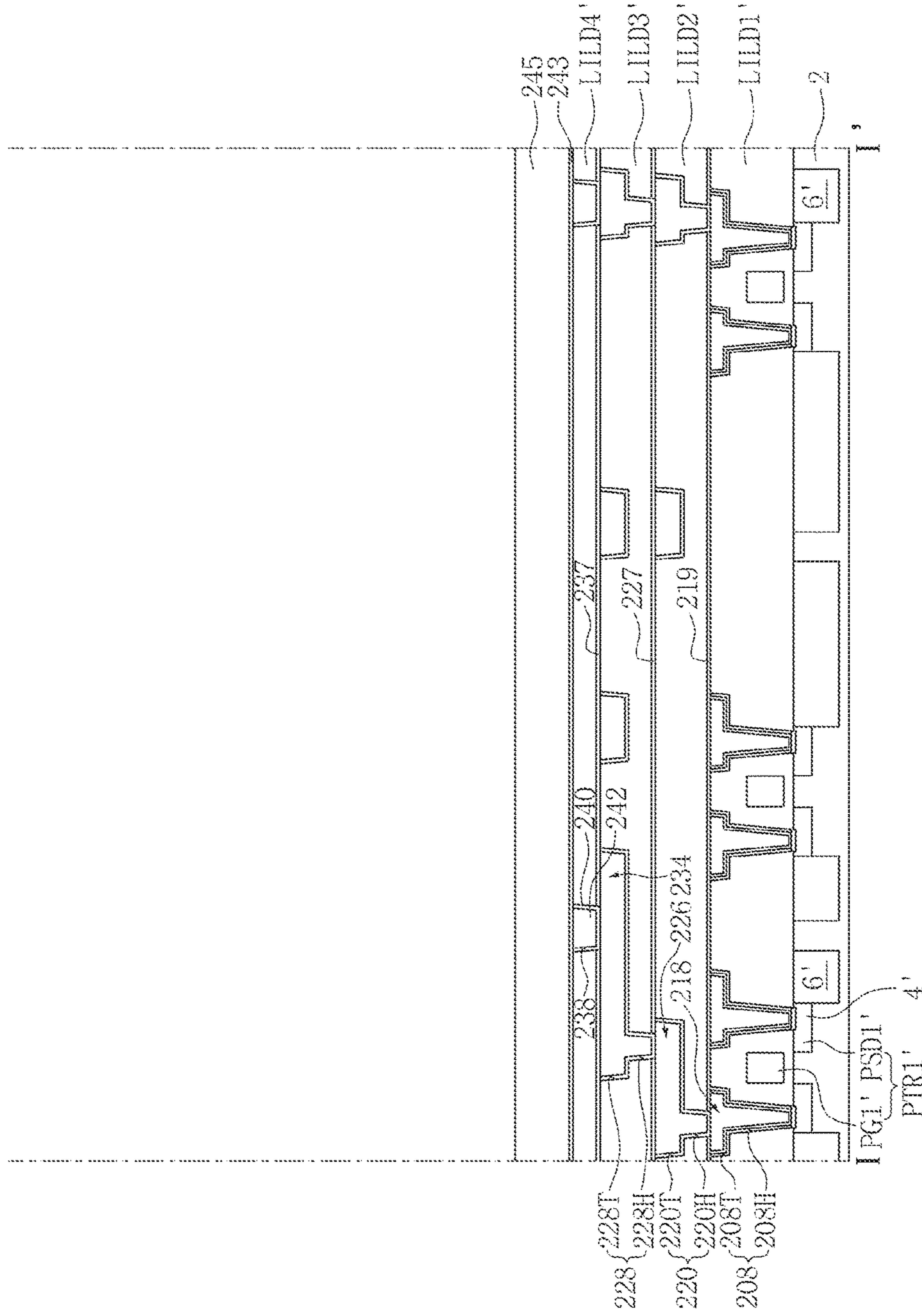


FIG. 15B

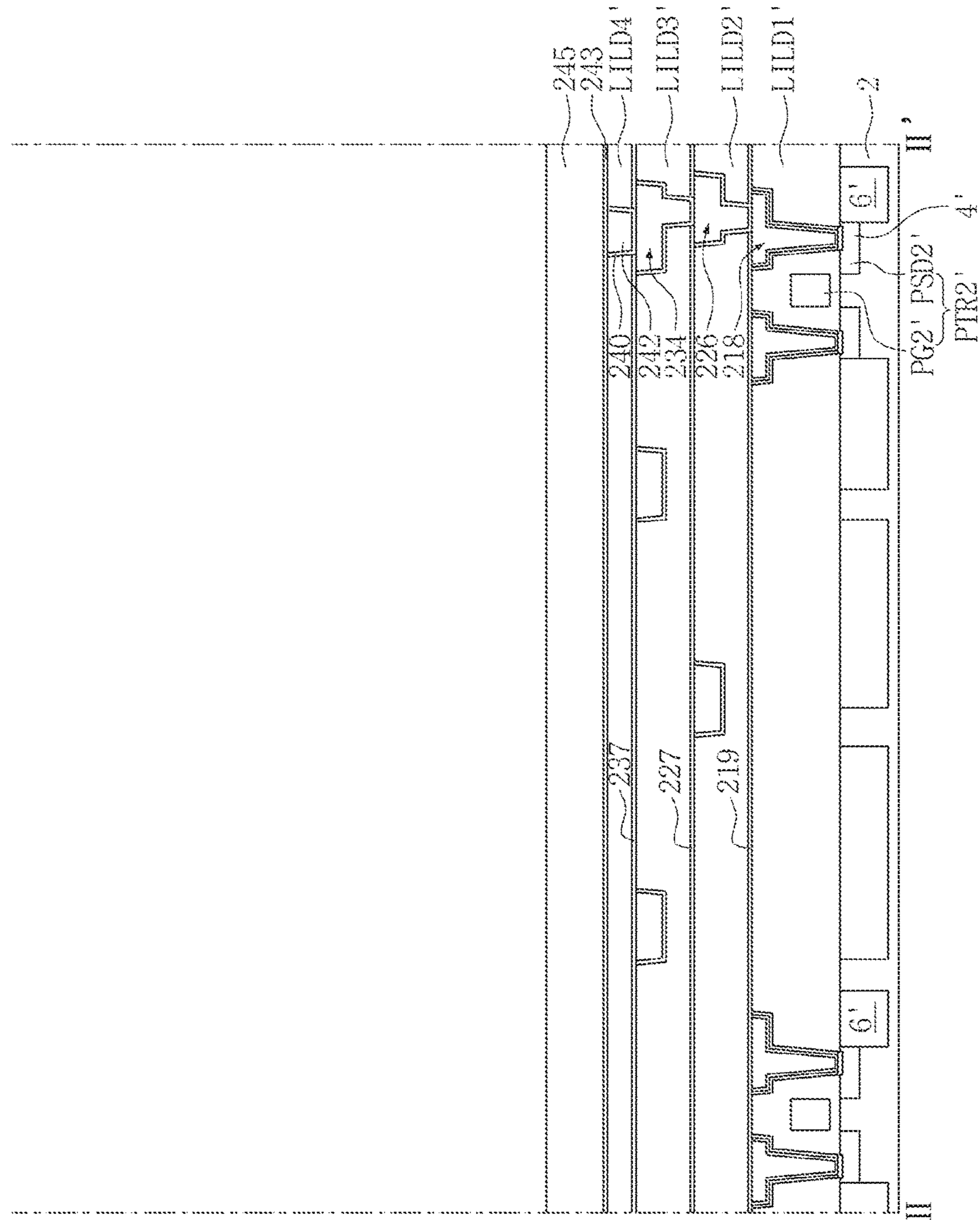


FIG. 16A

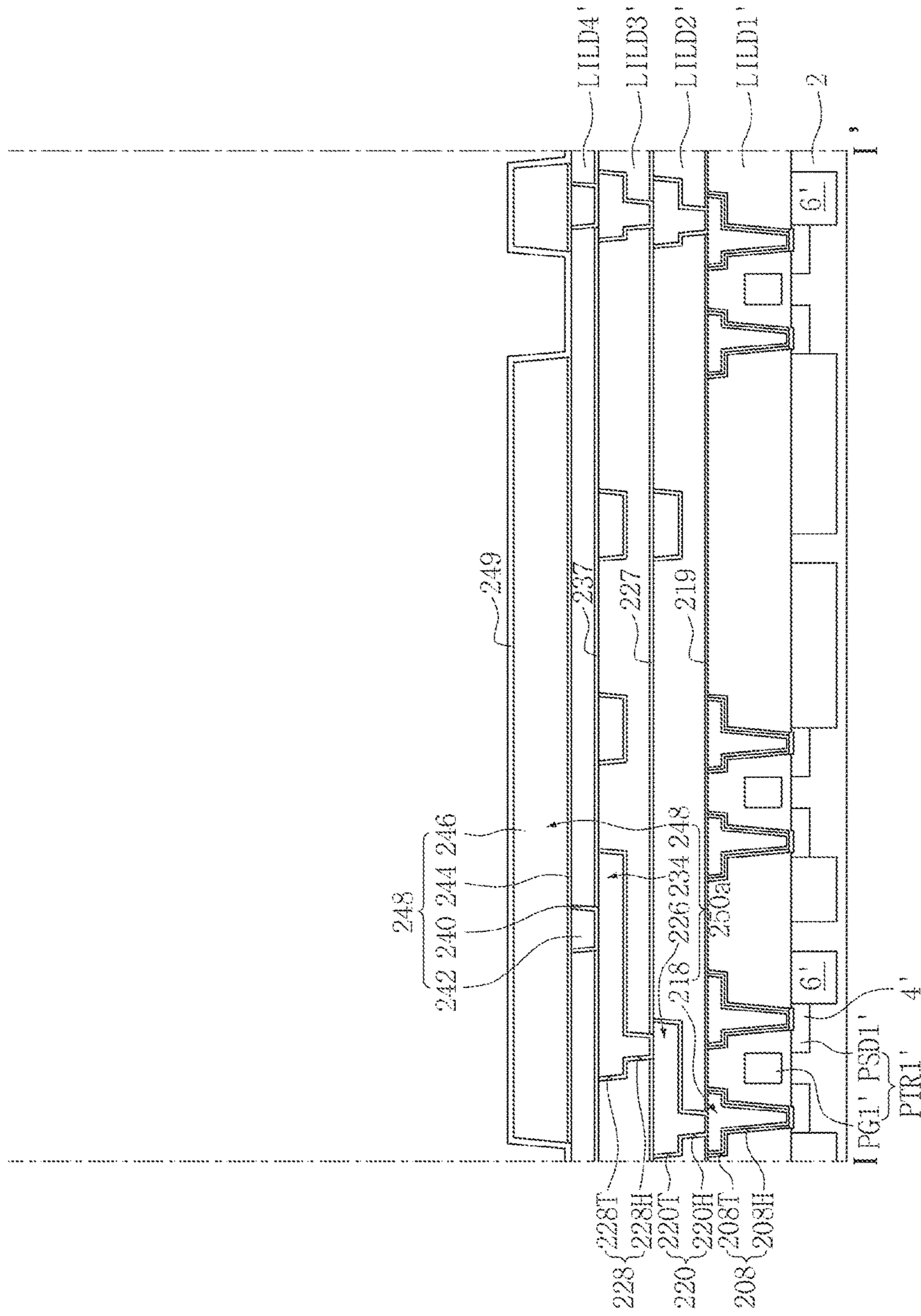


FIG. 16B

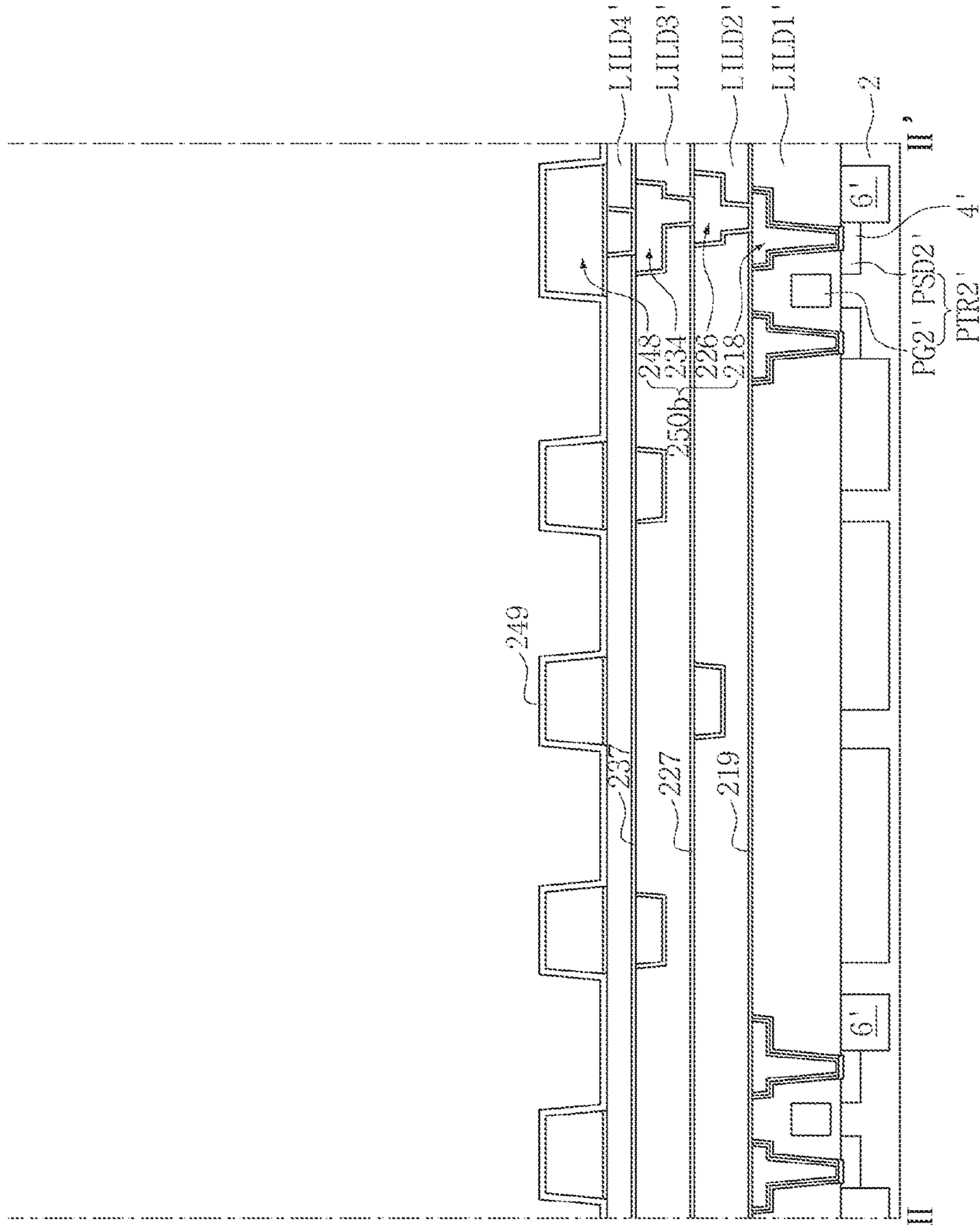


FIG. 17A

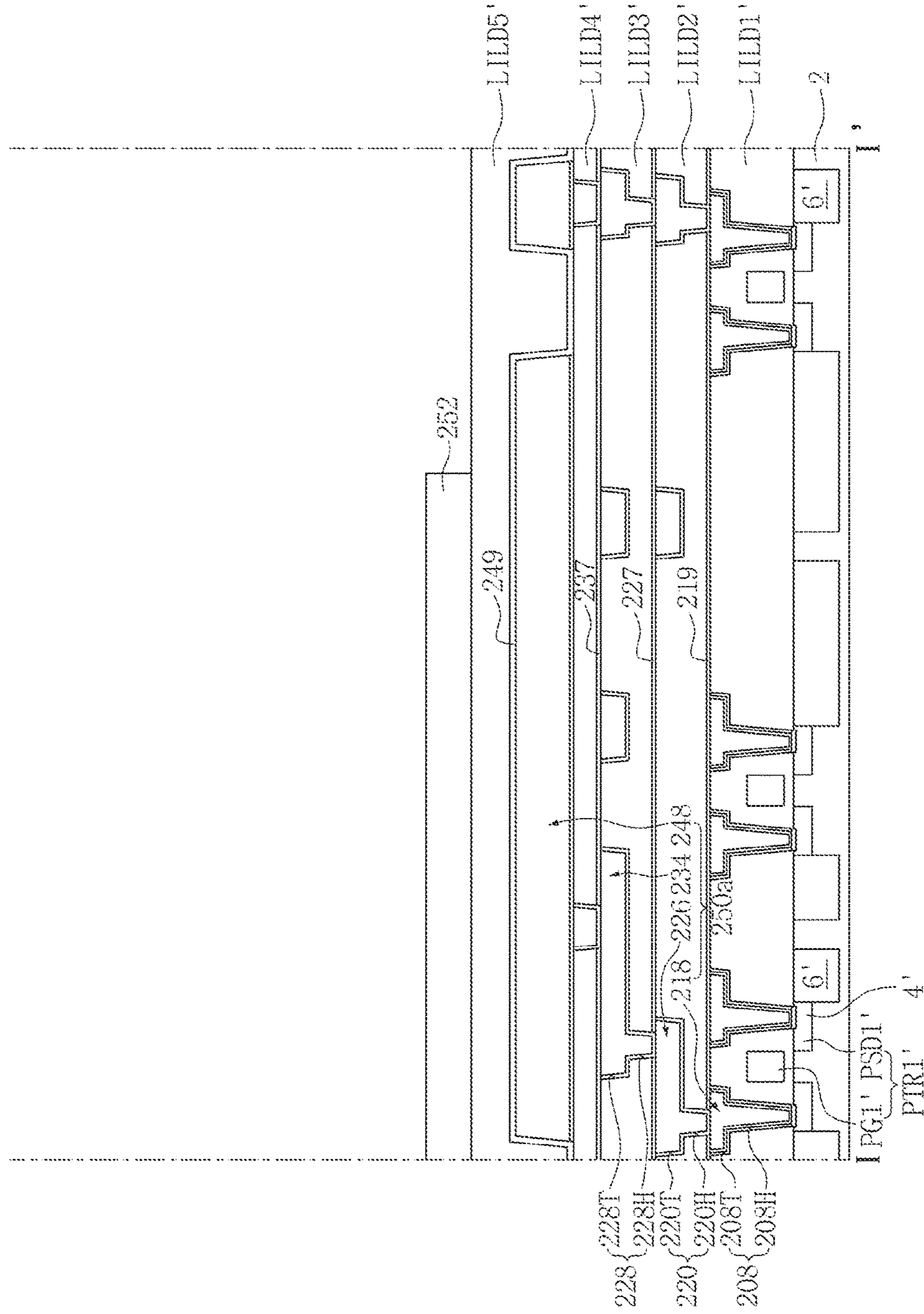


FIG. 17B

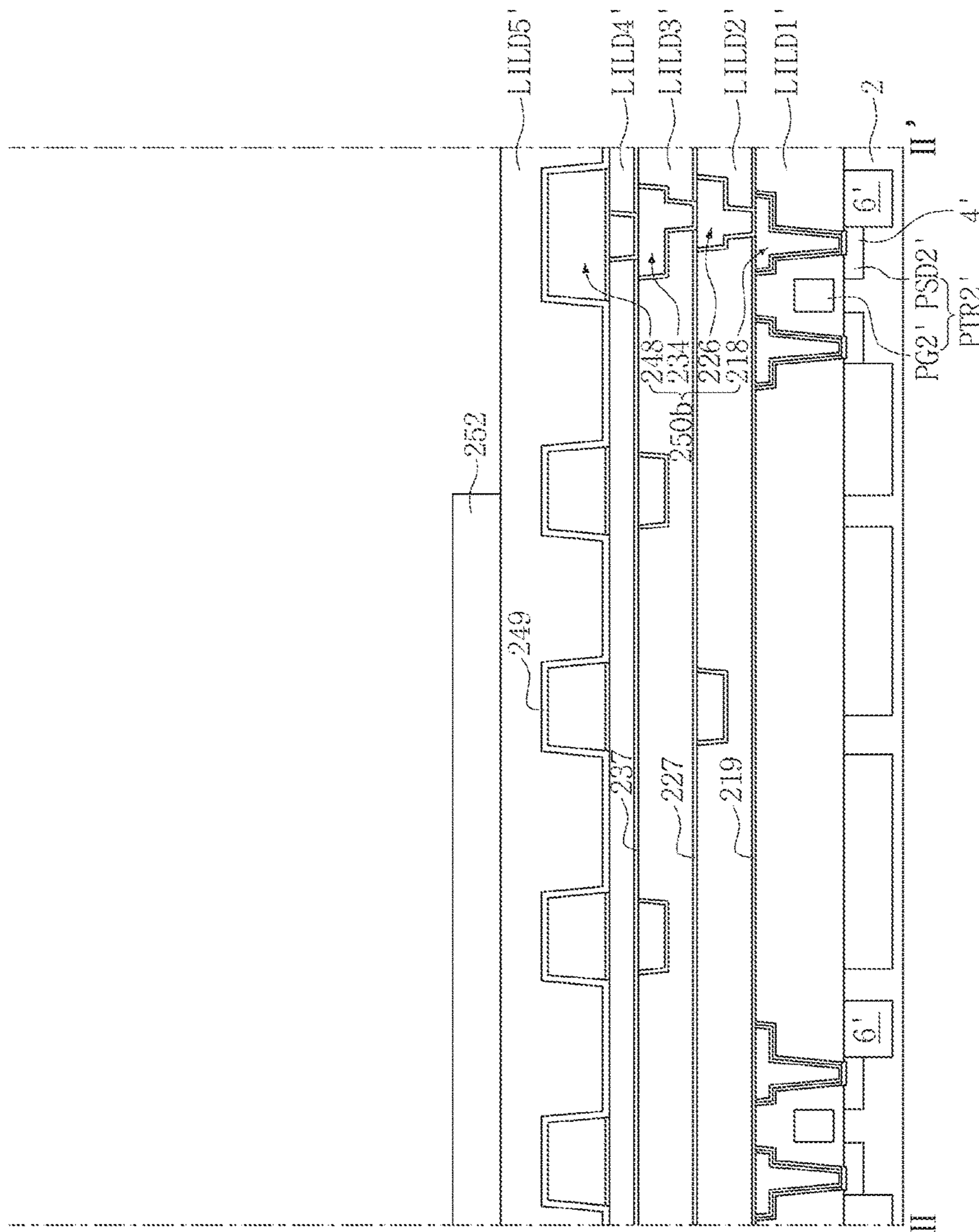


FIG. 18A

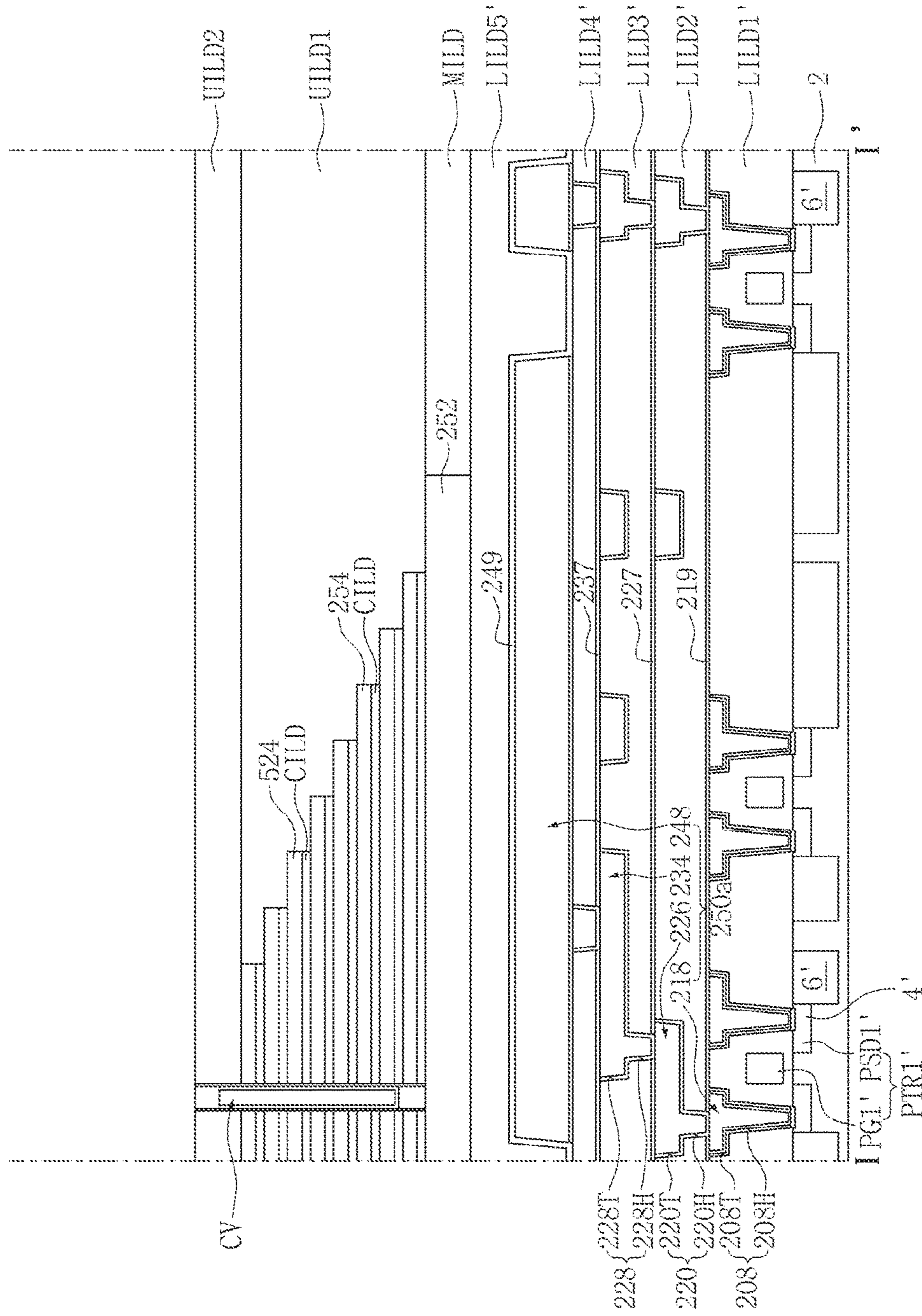


FIG. 18B

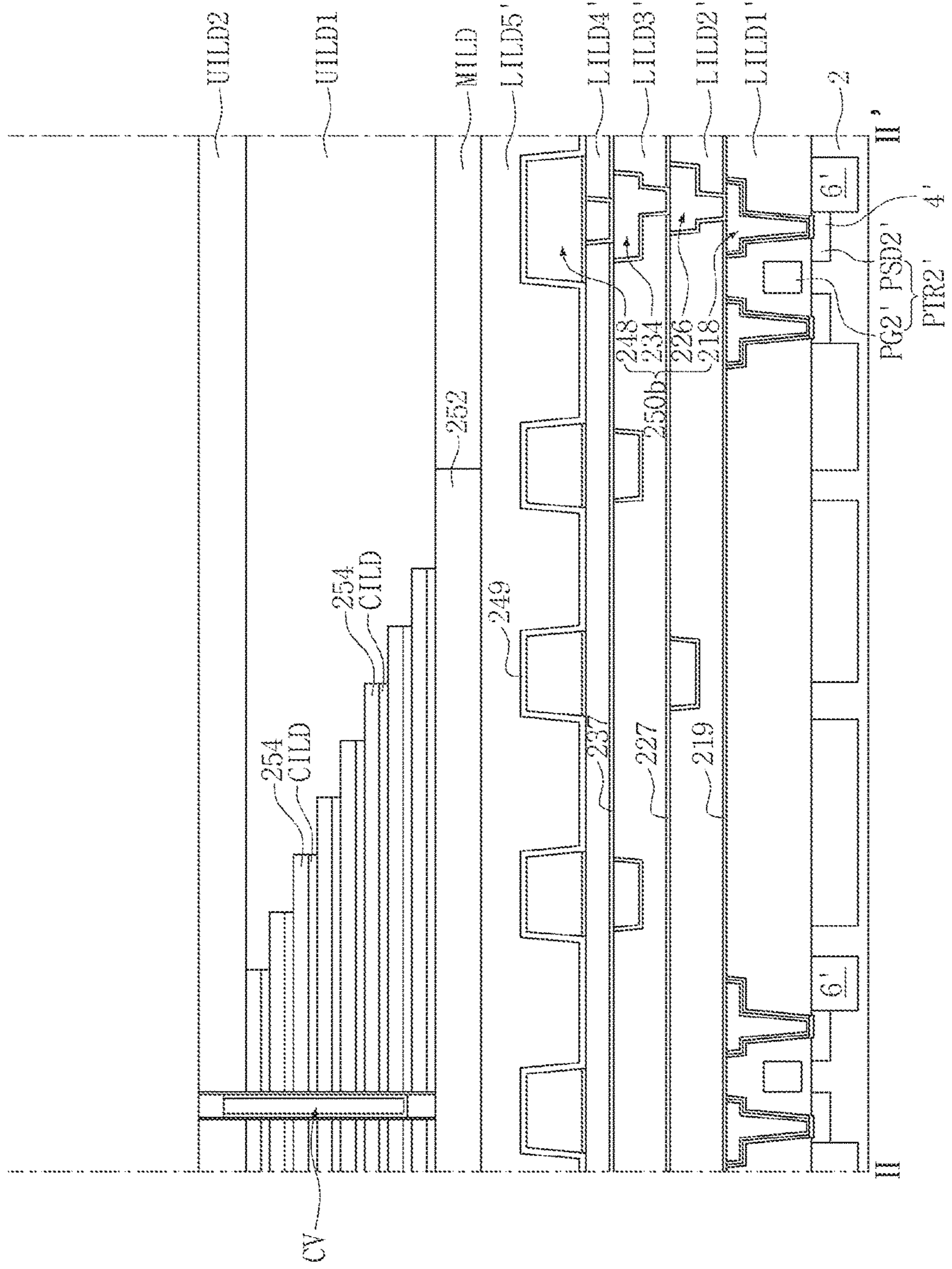


FIG. 19A

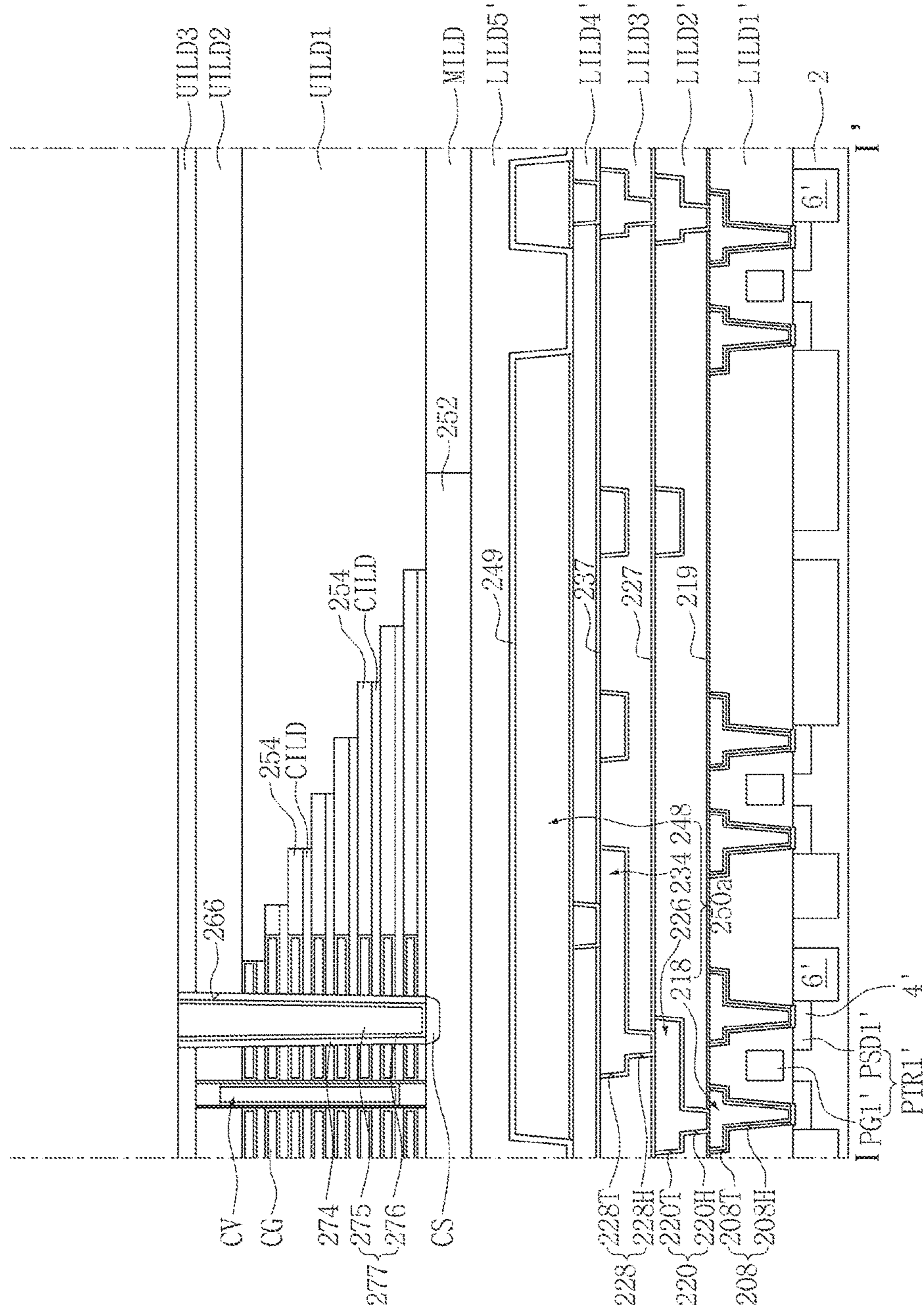


FIG. 19B

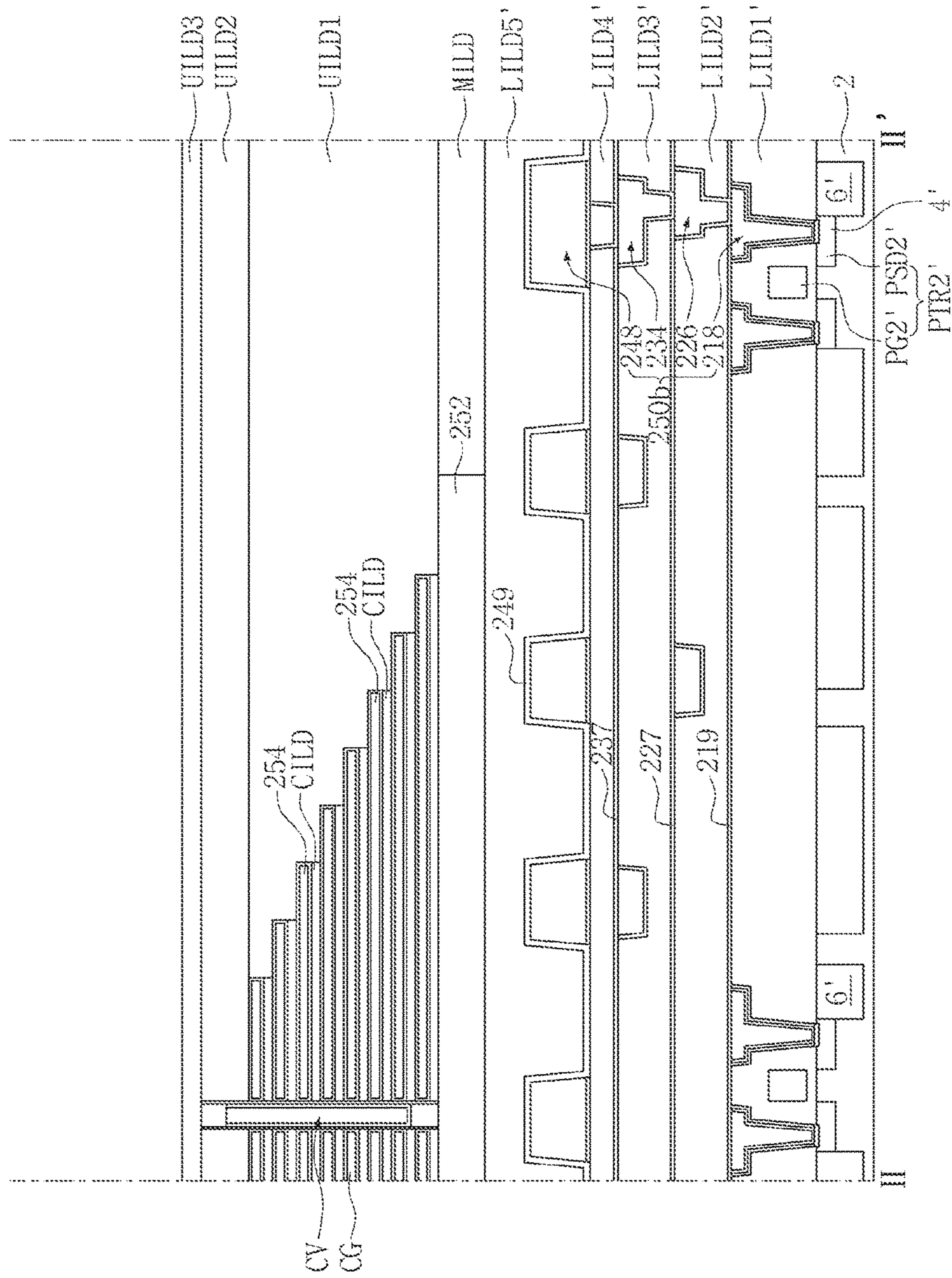


FIG. 20A

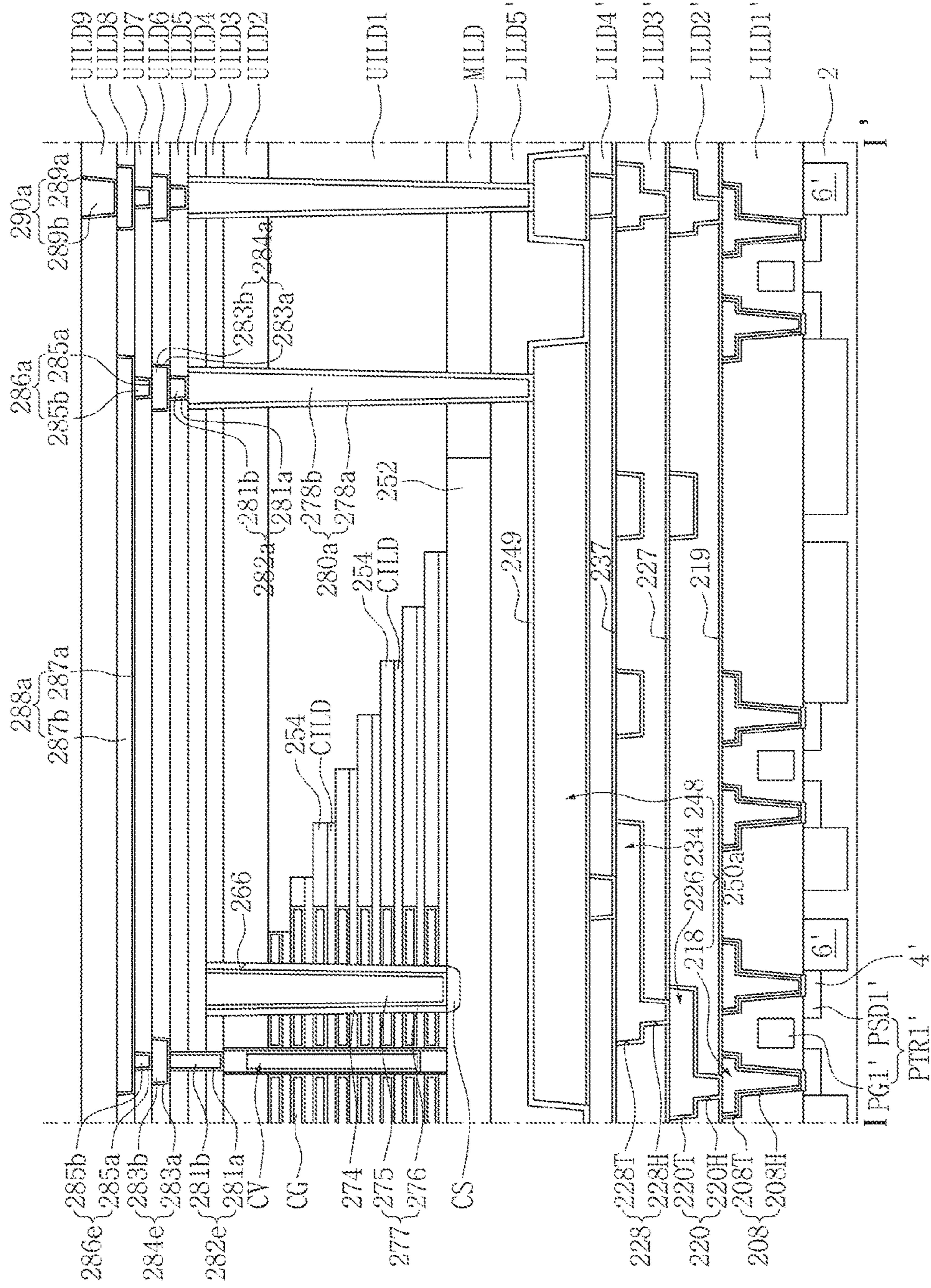


FIG. 20B

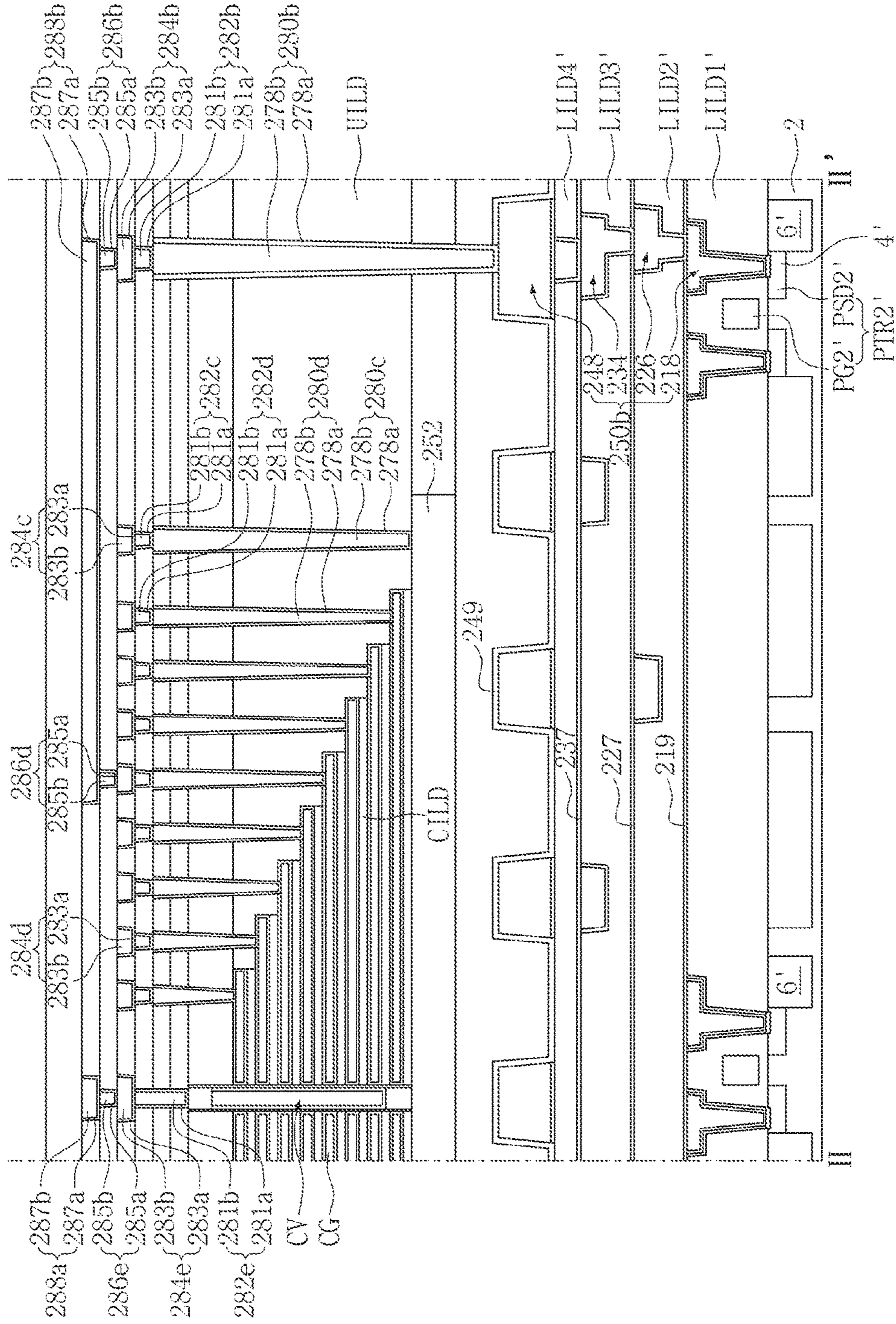


FIG. 21A

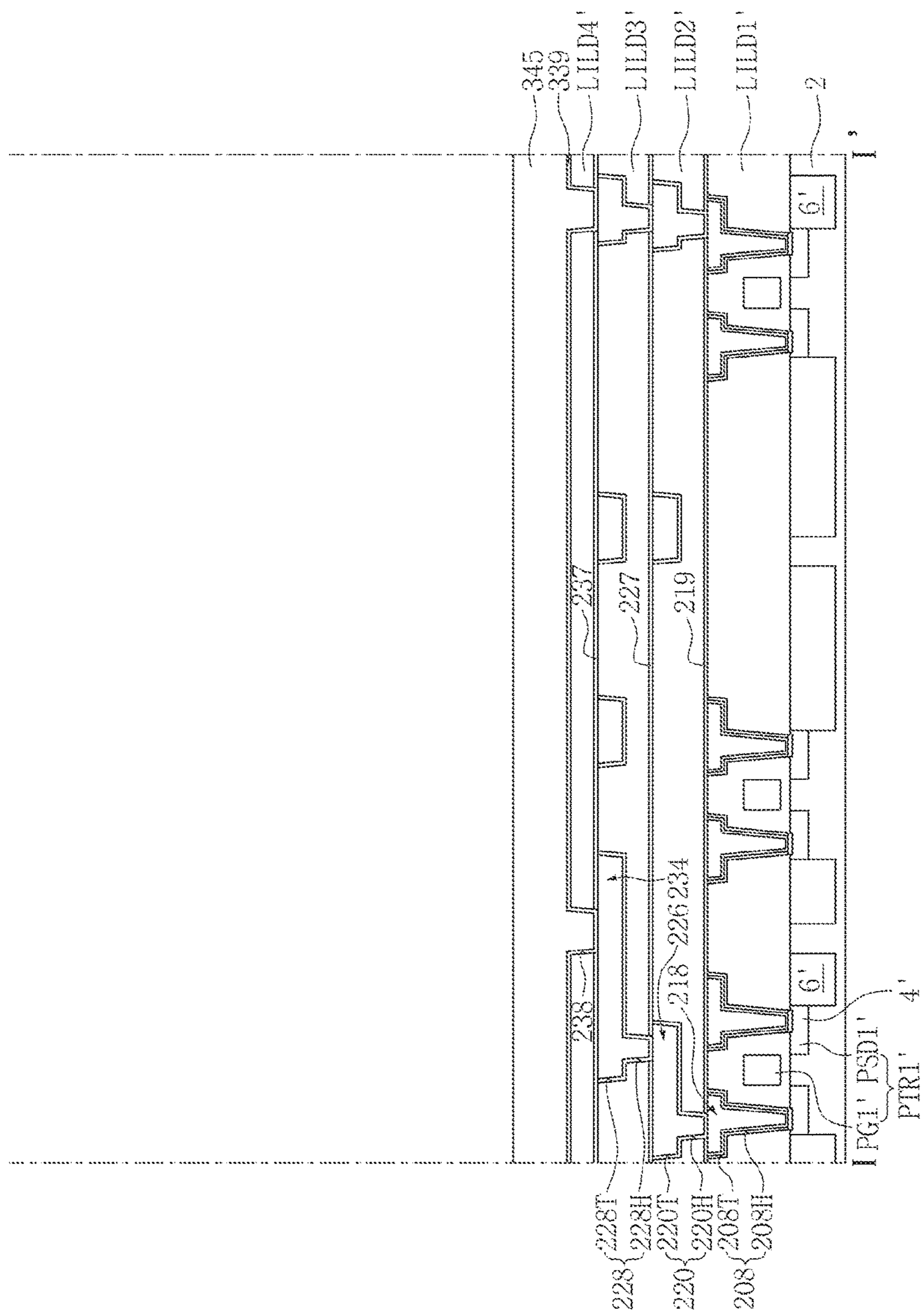


FIG. 21B

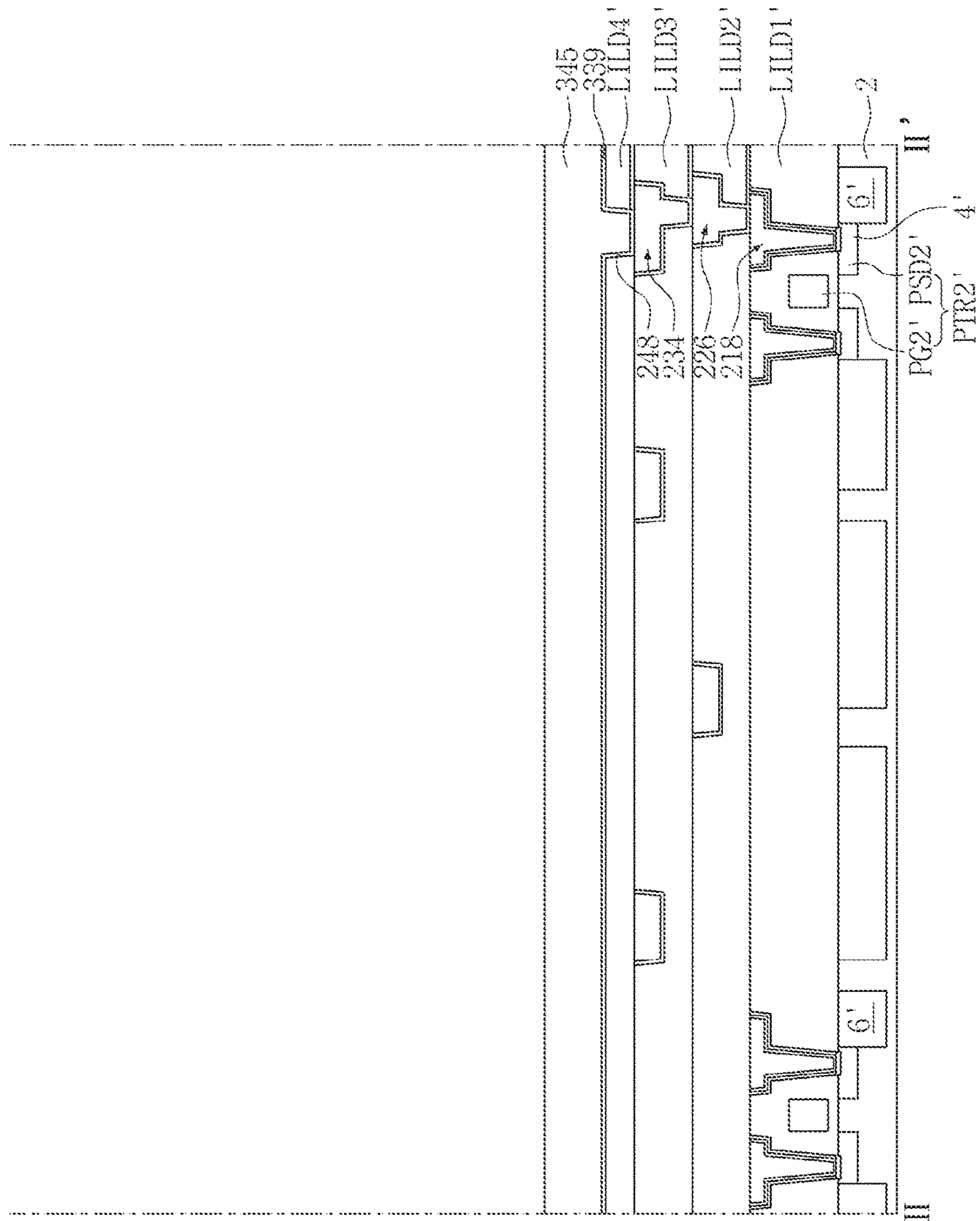


FIG. 22A

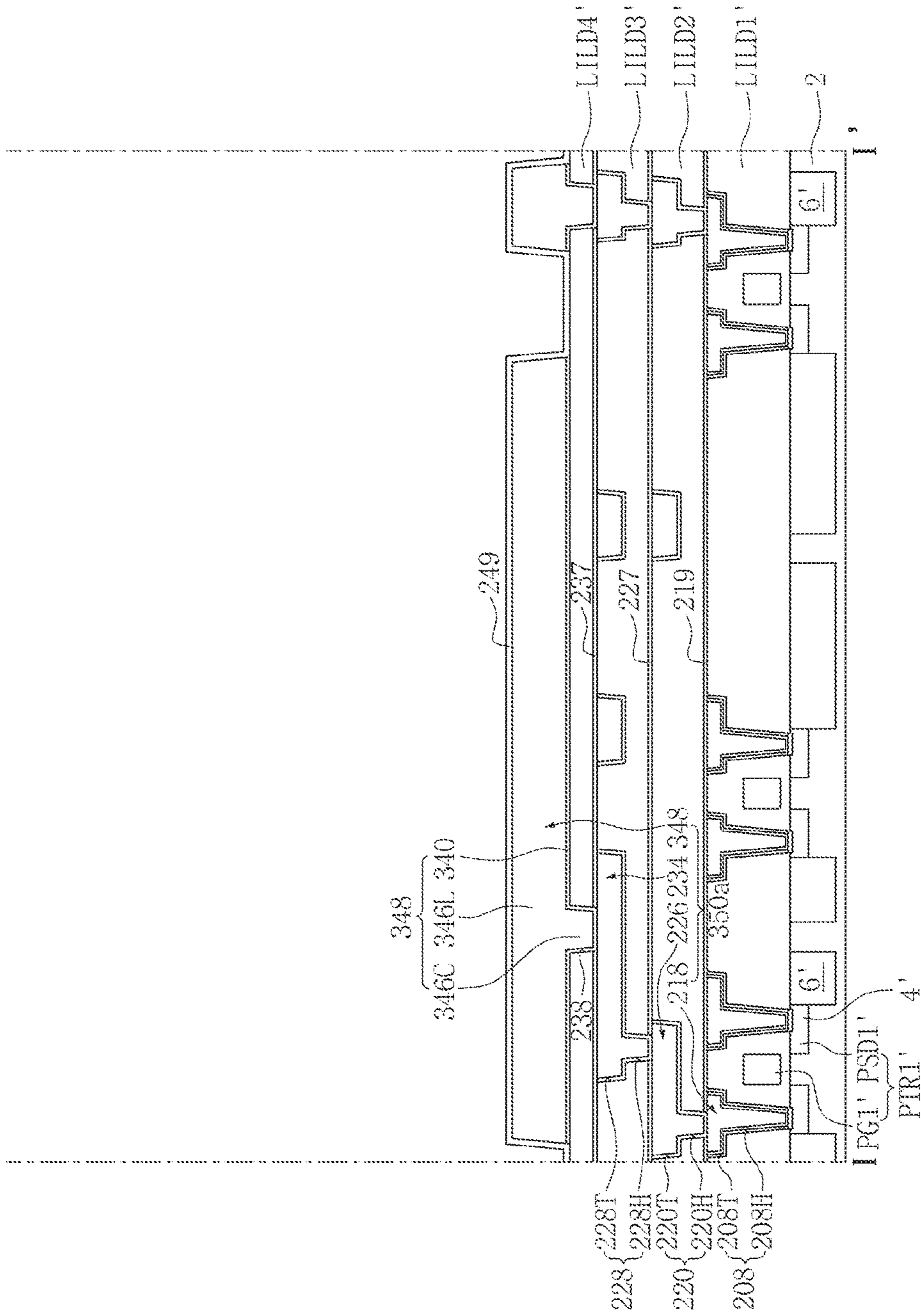


FIG. 22B

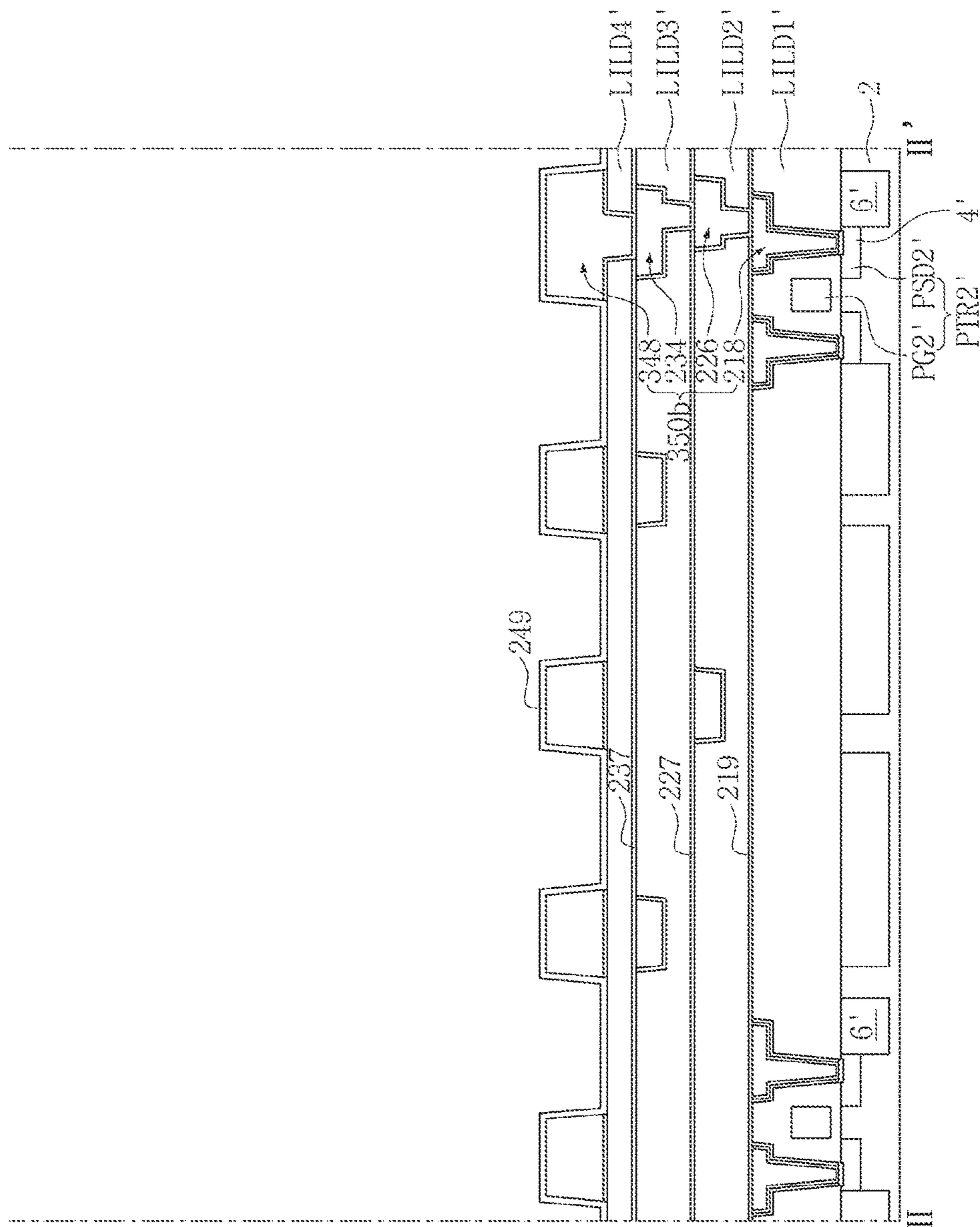


FIG. 23

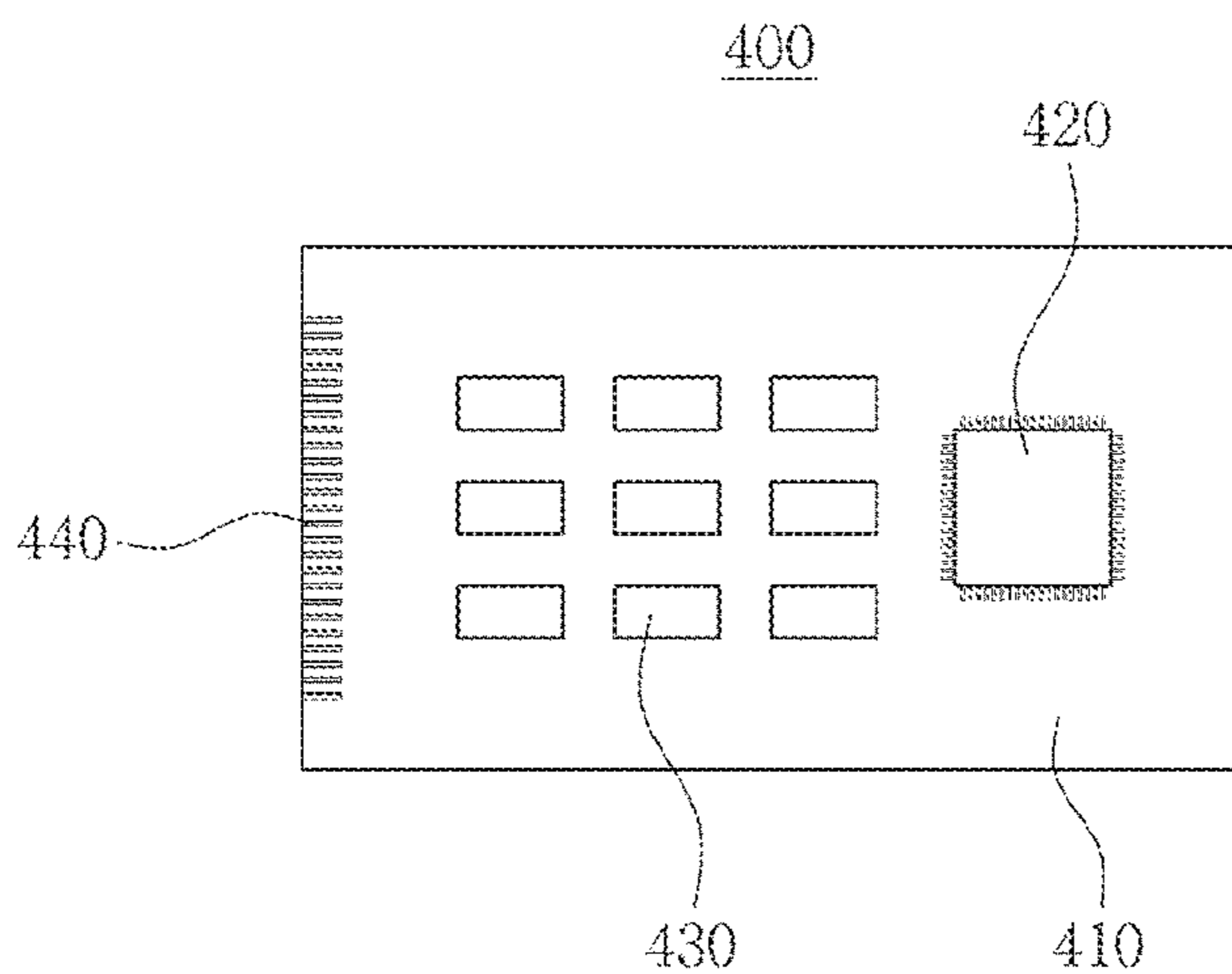


FIG. 24

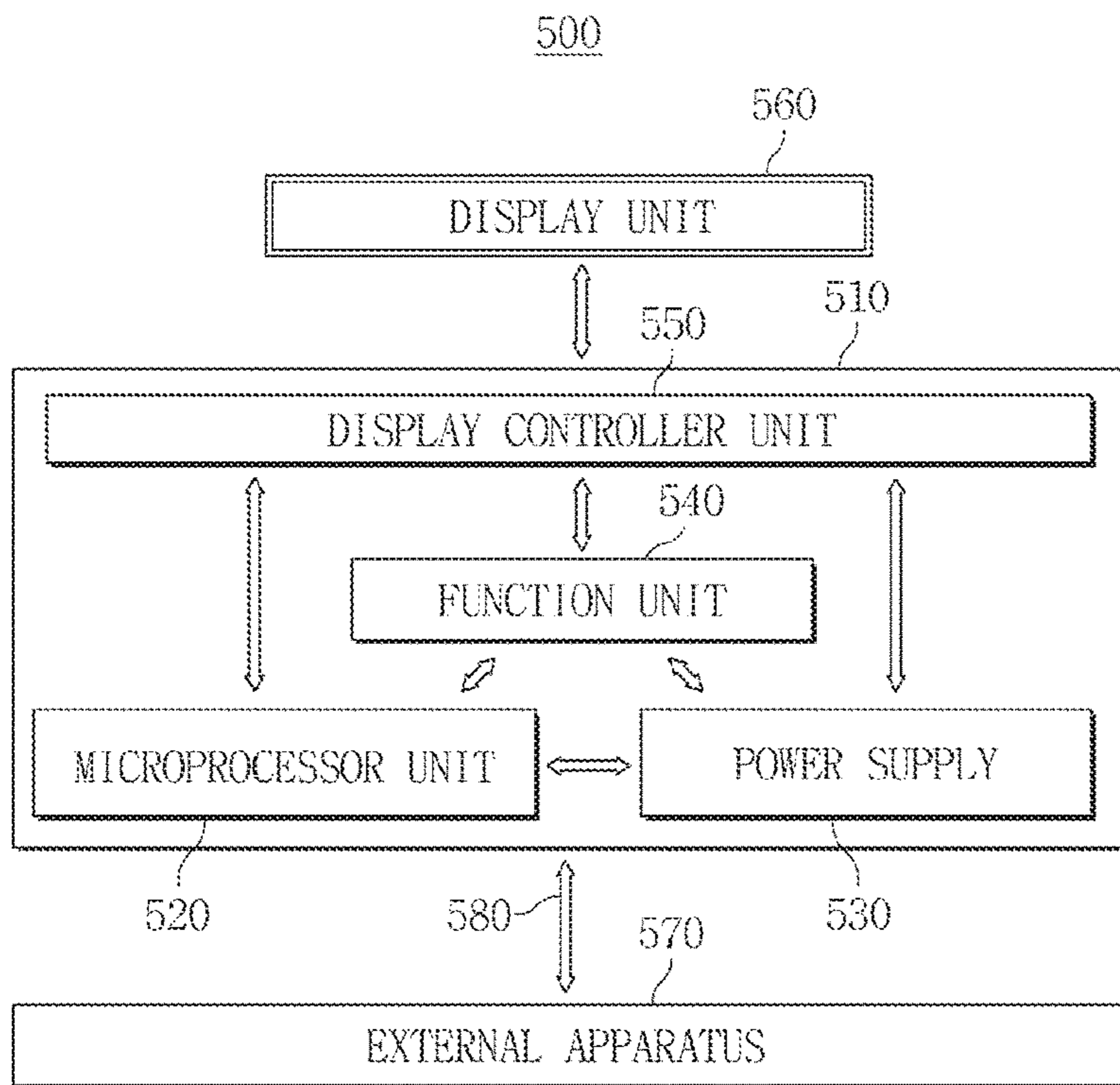
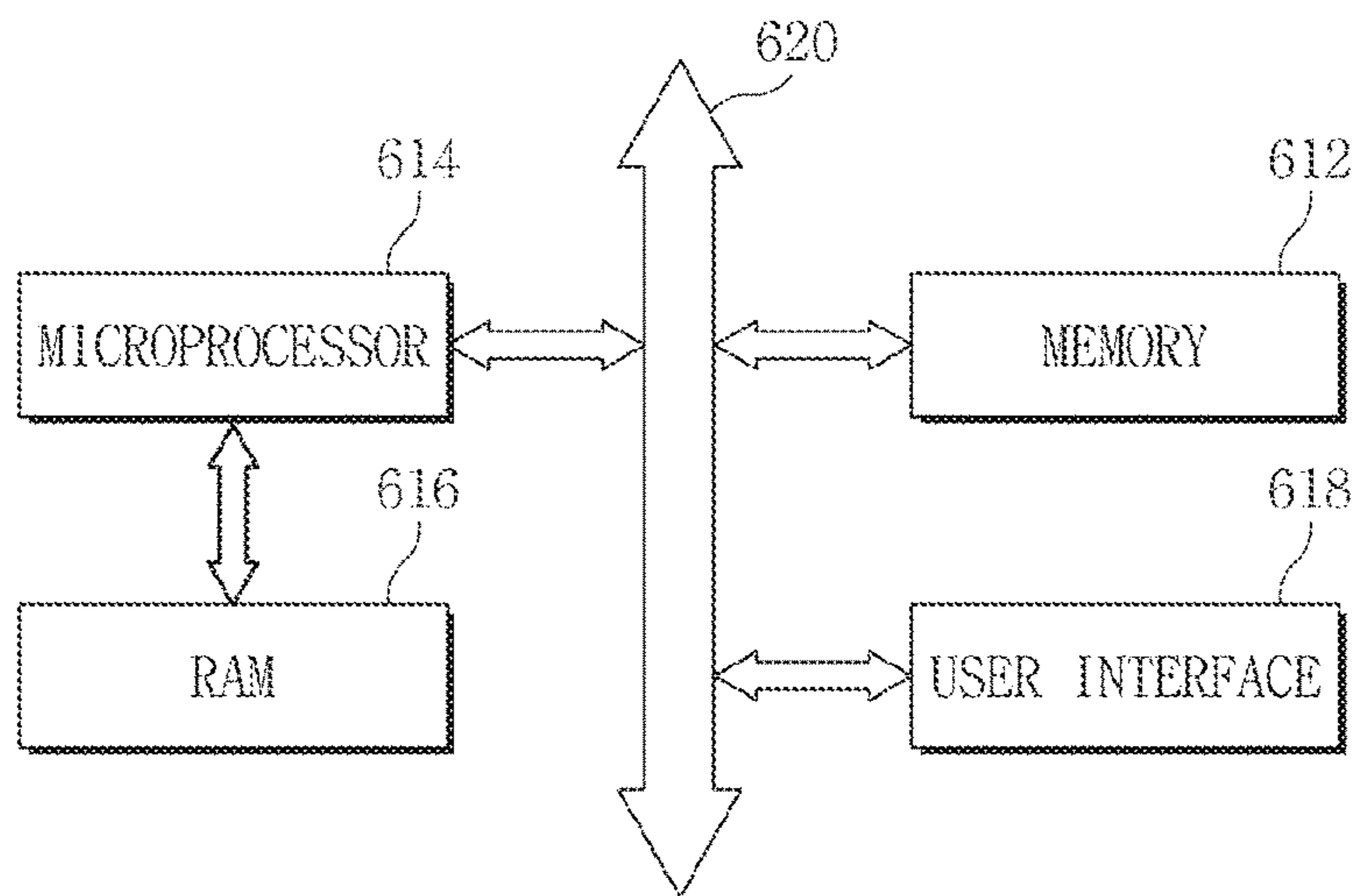


FIG. 25

600



SEMICONDUCTOR DEVICE HAVING INTERCONNECTION STRUCTURE

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation of U.S. application Ser. No. 15/201,922, filed Jul. 5, 2016, which claims priority under 35 U.S.C. § 119 to Korean Patent Application No. 10-2015-0096024 filed on Jul. 6, 2015, the disclosures of each of which are hereby incorporated by reference in their entirety.

BACKGROUND

Technical Field

Example embodiments of inventive concepts relate to a semiconductor device having an interconnection structure, a method of forming the semiconductor device, and electronic systems using the same.

Description of Related Art

In semiconductor devices such as NAND flash memories, a degree of integration is may affect the price of a semiconductor product. In order to increase the degree of integration, three-dimensionally arranged memory cells have been proposed, and the study for reducing the areas of interconnection structures capable of applying an electric signal to the three-dimensional memory cells and peripheral circuits has been conducted.

SUMMARY

In accordance with example embodiments of inventive concepts, a semiconductor device is provided. The semiconductor device includes a semiconductor substrate, a semiconductor pattern on the semiconductor substrate, a three-dimensional memory array on the semiconductor pattern, and a peripheral interconnection structure between the semiconductor pattern and the semiconductor substrate. The peripheral interconnection structure includes an upper interconnection structure and a lower interconnection structure. The lower interconnection structure is under the upper interconnection structure. The upper interconnection structure includes an upper interconnection and an upper barrier layer. The lower interconnection structure includes a lower interconnection and a lower barrier layer. The upper barrier layer is under a bottom surface of the upper interconnection. The upper barrier layer does not cover side surfaces of the upper interconnection. The lower barrier layer is under a bottom surface of the lower interconnection. The lower barrier layer covers side surfaces of the lower interconnection.

In example embodiments, a thickness of the upper interconnection may be greater than a thickness of the lower interconnection.

In example embodiments, the side surfaces of the upper interconnection may have positive slopes. The side surfaces of the lower interconnection may have negative slopes.

In example embodiments, the lower interconnection structure may further include a lower contact plug under the lower interconnection.

In example embodiments, the lower contact plug may be integrally formed with the lower interconnection.

In example embodiments, the lower barrier layer may extend on side surfaces and a bottom surface of the lower contact plug.

In example embodiments, the lower interconnection may further include a lower conductive layer. The lower conductive layer may be on the bottom surface and the side surfaces of the lower interconnection. The lower conductive layer may extend on side surfaces of the lower contact plug. The lower barrier layer may be between the lower conductive layer and the lower interconnection. The lower barrier layer may extend between the lower conductive layer and the lower contact plug.

In example embodiments, the upper interconnection structure may further include an upper contact plug between the upper interconnection and the lower interconnection.

In example embodiments, the upper contact plug may be integrally formed with the upper interconnection. The upper barrier layer may extend so as to cover side surfaces and a lower surface of the upper contact plug.

In example embodiments, the three-dimensional memory array may include a plurality of memory cells. Each of the memory cells may include a charge trap layer.

In example embodiments, the three-dimensional memory array may include a plurality of memory strings. The memory strings may be perpendicular to the semiconductor pattern.

In accordance with example embodiments of inventive concepts, a semiconductor device is provided. The semiconductor device includes a semiconductor substrate, a semiconductor pattern on the semiconductor substrate, a data storage element on the semiconductor pattern, and a peripheral interconnection structure between the semiconductor pattern and the semiconductor substrate. The peripheral interconnection structure includes a lower interconnection structure and an upper interconnection structure. The upper interconnection structure is on the lower interconnection structure. The lower interconnection structure includes a lower contact plug, a lower interconnection, and a lower barrier layer. The upper interconnection structure includes an upper contact plug, an upper interconnection, and an upper barrier layer. The upper interconnection has a greater thickness than a thickness of the lower interconnection.

In example embodiments, the lower contact plug may be under the lower interconnection. The upper contact plug may be under the upper interconnection. The lower barrier layer may cover side surfaces of the lower interconnection. The lower barrier layer may extend under a bottom surface of the lower interconnection. The upper barrier layer may not cover side surfaces of the upper interconnection. The upper barrier may be under a bottom surface of the upper interconnection.

In example embodiments, an angle between an upper surface of the upper interconnection and a side surface of the upper interconnection may be greater than an angle between an upper surface of the lower interconnection and a side surface of the lower interconnection.

In example embodiments, an angle between an upper surface of the upper interconnection and a side surface of the upper interconnection may be an obtuse angle. An angle between an upper surface of the lower interconnection and a side surface of the lower interconnection may be an acute angle.

In accordance with example embodiments of inventive concepts, a semiconductor device is provided. The semiconductor device includes a peripheral transistor on a semiconductor substrate, a semiconductor pattern transistor on the semiconductor substrate and overlapping the peripheral

transistor, a first three-dimensional memory array on the semiconductor pattern, and a peripheral interconnection structure between the semiconductor substrate and the semiconductor pattern and electrically connected to the peripheral transistor. The peripheral interconnection structure includes an upper interconnection structure and a lower interconnection structure under the upper interconnection structure, the upper interconnection structure includes an upper interconnection and an upper barrier layer. The lower interconnection structure includes a lower interconnection and a lower barrier layer. The upper barrier layer is under a bottom surface of the upper interconnection and exposes side surfaces of the upper interconnection. The lower barrier layer is under a bottom surface of the lower interconnection and covers side surfaces of the lower interconnection.

According to example embodiments, a semiconductor device includes a peripheral interconnection structure, a semiconductor pattern on the peripheral interconnection structure, and a memory array on the semiconductor pattern. The peripheral interconnection structure includes an upper interconnection structure on a lower interconnection structure. The lower interconnection structure includes a lower barrier layer that contacts a side surface of a lower contact plug, and a lower interconnection on the lower contact plug. The upper interconnection structure includes an upper interconnection on an upper contact plug and an upper barrier layer. The upper interconnection is on top of the upper barrier layer. The upper contact plug is one of spaced apart from a lower surface of the upper interconnection and protruding from the lower surface of the upper interconnection. The upper interconnection has a different stress characteristic than the lower contact plug.

In example embodiments, a side surface of the upper interconnection may have a positive slope and the side surface of the lower interconnection may have a negative slope.

In example embodiments, the upper interconnection may include a metal layer having a different stress characteristic than a metal layer in the lower interconnection.

In example embodiments, a thickness of the upper interconnection may be greater than a thickness of the lower interconnection.

In example embodiments, the memory array may be a three-dimensional memory array on the semiconductor pattern. The three-dimensional memory array may include a plurality of cell gate conductive patterns stacked on top of each other and a plurality of cell vertical structures penetrating the cell gate conductive patterns. The upper barrier layer may be arranged so it does not cover side surfaces of the upper interconnection. The lower interconnection may be on the lower barrier layer.

Details of example embodiments are included in detailed explanations and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other features of inventive concepts will be apparent from the more particular description of non-limiting embodiments of inventive concepts, as illustrated in the accompanying drawings in which like reference characters refer to the same (and/or or like) parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the features of inventive concepts. In the drawings:

FIG. 1 is a cross-sectional view showing an example of a semiconductor device in accordance with example embodiments of inventive concepts;

FIG. 2 is an enlarged cross-sectional view showing some components of FIG. 1;

FIG. 3 is an enlarged cross-sectional view showing the other components of FIG. 1;

FIGS. 4 and 5 are cross-sectional views showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts;

FIG. 6A is a layout showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts;

FIG. 6B is a plan view showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts;

FIGS. 7A and 7B are cross-sectional views showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts;

FIG. 8 is an enlarged cross-sectional view showing some components of FIG. 7A;

FIGS. 9A and 9B are cross-sectional views showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts;

FIG. 10 is an enlarged cross-sectional view showing some components of FIG. 9A;

FIGS. 11A to 20B are cross-sectional views showing an example of a method of forming a semiconductor device in accordance with example embodiments of inventive concepts;

FIGS. 21A to 22B are cross-sectional views showing a modified example of a method of forming a semiconductor device in accordance with example embodiments of inventive concepts;

FIG. 23 is a schematic view showing a semiconductor module according to example embodiments of inventive concepts;

FIG. 24 is a conceptual block diagram showing an electronic system according to example embodiments of inventive concepts; and

FIG. 25 is a schematic block diagram showing an electronic system according to example embodiments of inventive concepts.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

Example embodiments will now be described more fully with reference to the accompanying drawings, in which some example embodiments are shown. Example embodiments, may, however, be embodied in many different forms and should not be construed as being limited to the embodiments set forth herein; rather, these example embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of example embodiments of inventive concepts to those of ordinary skill in the art. In the drawings, the thicknesses of layers and regions are exaggerated for clarity. Like reference characters and/or numerals in the drawings denote like elements, and thus their description may not be repeated.

Further, it will be understood that when a layer is referred to as being “on” another layer or a substrate, the layer may be formed directly on the other layer or the substrate, or there may be an intervening layer therebetween. It will be understood that when an element is referred to as being “connected” or “coupled” to another element, it can be directly connected or coupled to the other element or intervening elements may be present. In contrast, when an element is referred to as being “directly connected” or “directly coupled” to another element, there are no inter-

vening elements present. Other words used to describe the relationship between elements or layers should be interpreted in a like fashion (e.g., “between” versus “directly between,” “adjacent” versus “directly adjacent,” “on” versus “directly on”). As used herein the term “and/or” includes any and all combinations of one or more of the associated listed items.

Terms such as “top,” “bottom,” “upper,” “lower,” “above,” “below,” and the like are used herein to describe the relative positions of elements or features. It will be understood that such descriptions are intended to encompass different orientations in use or operation in addition to orientations depicted in the drawings. For example, when an upper part of a drawing is referred to as a “top” and a lower part of a drawing as a “bottom” for the sake of convenience, in practice, the “top” may also be called a “bottom” and the “bottom” a “top” without departing from the teachings of example embodiments of inventive concepts.

Furthermore, throughout this disclosure, directional terms such as “upper,” “intermediate,” “lower,” and the like may be used herein to describe the relationship of one element or feature with another, and example embodiments of inventive concepts should not be limited by these terms. It will be understood that the spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. For example, if the device in the figures is turned over, elements described as “below” or “beneath” other elements or features would then be oriented “above” the other elements or features. Thus, the term “below” can encompass both an orientation of above and below. The device may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein interpreted accordingly. Additionally, these terms such as “upper,” “intermediate,” “lower,” and the like may be replaced by other terms such as “first,” “second,” “third,” and the like to describe the elements and features.

It will be understood that, although the terms “first,” “second,” etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. Thus, a first element could be termed a second element without departing from the teachings of example embodiments of inventive concepts.

The terminology used herein to describe example embodiments of inventive concepts are not intended to limit the scope of example embodiments of inventive concepts. As used herein, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes,” and/or “including,” when used herein, specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof. Expressions such as “at least one of,” when preceding a list of elements, modify the entire list of elements and do not modify the individual elements of the list.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which example embodiments of inventive concepts belong. It will be further understood that terms, such as those defined in commonly used dictionaries, should be interpreted as having a meaning that is consistent with their meaning in the

context of the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

Example embodiments are described herein with reference to cross-sectional illustrations that are schematic illustrations of idealized embodiments (and intermediate structures) of example embodiments. As such, variations from the shapes of the illustrations as a result, for example, of manufacturing techniques and/or tolerances, are to be expected. Thus, example embodiments should not be construed as limited to the particular shapes of regions illustrated herein but are to include deviations in shapes that result, for example, from manufacturing. For example, an etched region or an implanted region illustrated as a rectangle may have rounded or curved features. Thus, the regions illustrated in the figures are schematic in nature and their shapes are not intended to illustrate the actual shape of a region of a device and are not intended to limit the scope of example embodiments.

FIG. 1 is a cross-sectional view showing an example of a semiconductor device in accordance with example embodiments of inventive concepts, and FIGS. 2 and 3 are views showing some components of FIG. 1. First, the semiconductor device in accordance with example embodiments of inventive concepts will be described with reference to FIG. 1.

Referring to FIG. 1, a semiconductor substrate 2 may be provided. The semiconductor substrate 2 may be a semiconductor substrate formed of silicon, such as single crystal silicon, but not limited thereto. An isolation region 6, which defines an active region 4, may be disposed on the semiconductor substrate 2. The isolation region 6 may be a shallow trench isolation (STI).

A circuit may be disposed on the semiconductor substrate 2. The circuit may include a first peripheral transistor PTR1 and a second peripheral transistor PTR2. The first peripheral transistor PTR1 may include a first peripheral gate PG1 and a first source/drain region PSD1, and the second peripheral transistor PTR2 may include a second peripheral gate PG2 and a second source/drain region PSD2.

A lower interlayer insulating layer LILD may be disposed on the semiconductor substrate 2. The lower interlayer insulating layer LILD may be formed with a plurality of layers. For example, the lower interlayer insulating layer LILD may include a first lower interlayer insulating layer LILD1, a second lower interlayer insulating layer LILD2, a third lower interlayer insulating layer LILD3, and a fourth lower interlayer insulating layer LILD4, which are sequentially stacked in a direction Z perpendicular to the semiconductor substrate 2.

A lower capping layer 19 may be disposed between the first lower interlayer insulating layer LILD1 and the second lower interlayer insulating layer LILD2. An intermediate capping layer 27 may be disposed between the second lower interlayer insulating layer LILD2 and the third lower interlayer insulating layer LILD3. An upper capping layer 49 may be disposed between the third lower interlayer insulating layer LILD3 and the fourth lower interlayer insulating layer LILD4.

The lower interlayer insulating layer LILD may be formed with an oxide-based insulating layer, for example, a silicon oxide layer or a low-k dielectric material layer, and the lower, intermediate, and upper capping layers 19, 27, and 49 may be formed with a nitride-based insulating layer, for example, a silicon nitride layer.

A first peripheral interconnection structure 50a and a second peripheral interconnection structure 50b may be

disposed on the semiconductor substrate **2**. The first and second peripheral interconnection structures **50a** and **50b** may be disposed in the lower interlayer insulating layer LILD.

The first peripheral interconnection structure **50a** may be electrically connected to the first peripheral transistor PTR1, and the second peripheral interconnection structure **50b** may be electrically connected to the second peripheral transistor PTR2. For example, the first peripheral interconnection structure **50a** may be electrically connected to the first source/drain region PSD1 of the first peripheral transistor PTR1, and the second peripheral interconnection structure **50b** may be electrically connected to the second source/drain region PSD2 of the second peripheral transistor PTR2.

Each of the first and second peripheral interconnection structures **50a** and **50b** may include a lower interconnection structure **18**, an upper interconnection structure **48** disposed on the lower interconnection structure **18**, and an intermediate interconnection structure **26** disposed between the lower interconnection structure **18** and the upper interconnection structure **48**.

Throughout this specification, terms such as “upper,” “intermediate,” “lower,” and the like may be used herein to distinguish the relative locations of elements from one another, and example embodiments of inventive concepts should not be limited by these terms. Therefore, these terms such as “upper,” “intermediate,” “lower,” and the like may be replaced by other terms such as “first,” “second,” “third,” and the like to describe the elements. For example, terms such as “upper interconnection” and “intermediate interconnection” used to distinguish relative positions thereof may be replaced by terms such as “first interconnection” and “second connection” or terms such as “upper interconnection” and “lower interconnection.”

The lower interconnection structure **18**, the intermediate interconnection structure **26**, and the upper interconnection structure **48**, which constitute the first peripheral interconnection structure **50a** will be described with reference to FIGS. 1 and 2.

Referring to FIGS. 1 and 2, the lower interconnection structure **18** may be a damascene interconnection structure which fills a lower opening **8** in the first lower interlayer insulating layer LILD1 with a conductive material. The lower opening **8** may include a lower contact hole **8H** which exposes the first source/drain region PSD1 and a lower interconnection trench **8T** disposed on the lower contact hole **8H**.

The lower interconnection structure **18** may include a lower contact plug **16C**, a lower interconnection **16L**, a lower conductive layer **12**, and a lower barrier layer **14**. The lower interconnection **16L** may be disposed on the lower contact plug **16C**. The lower contact plug **16C** may be disposed in the lower contact hole **8H** and the lower interconnection **16L** may be disposed in the lower interconnection trench **8T**.

The lower contact plug **16C** and the lower interconnection **16L** may be integrally formed. The lower contact plug **16C** and the lower interconnection **16L** may be formed of the same material. For example, the lower contact plug **16C** and the lower interconnection **16L** may be formed of a refractory metal. The lower contact plug **16C** and the lower interconnection **16L** may be formed of a refractory metal having a tensile stress characteristic (e.g., tungsten) and the lower contact plug **16C** and the lower interconnection **16L** may be formed using a chemical vapor deposition (CVD) process.

The lower conductive layer **12** may be disposed on side surfaces of the lower contact plug **16C** and may extend on

a bottom surface and side surfaces of the lower interconnection **16L**. The lower barrier layer **14** may be interposed between the lower conductive layer **12** and the lower contact plug **16C** and between the lower conductive layer **12** and the lower interconnection **16L** and may extend on a bottom surface of the lower contact plug **16C**. The lower barrier layer **14** may cover the bottom surface and the side surfaces of the lower contact plug **16C** and the bottom surface and the side surfaces of the lower interconnection **16L**.

A metal-silicide layer **10** may be disposed under the lower interconnection structure **18**. The metal-silicide layer **10** may be a material made of a metal material constituting the lower conductive layer **12** (e.g., Ti) and an element constituting the semiconductor substrate **2** (e.g., Si).

In example embodiments, the lower capping layer **19** may cover an upper surface of the lower interconnection **16L** of the lower interconnection structure **18**.

The intermediate interconnection structure **26** may be a damascene interconnection structure which fills an intermediate opening **20** in the second lower interlayer insulating layer LILD2 with a conductive material. The intermediate opening **20** may include an intermediate contact hole **20H** which exposes the lower interconnection **16L** and an intermediate interconnection trench **20T** disposed on the intermediate contact hole **20H**.

The intermediate interconnection structure **26** may include an intermediate contact plug **24C**, an intermediate interconnection **24L**, and an intermediate barrier layer **22**. The intermediate contact plug **24C** may be disposed in the intermediate contact hole **20H** and the intermediate interconnection **24L** may be disposed in the intermediate interconnection trench **20T**.

The intermediate interconnection **24L** may be disposed on the intermediate contact plug **24C**. The intermediate contact plug **24C** and the intermediate interconnection **24L** may be integrally formed. The intermediate contact plug **24C** and the intermediate interconnection **24L** may be formed of the same material. For example, the intermediate contact plug **24C** and the intermediate interconnection **24L** may be formed of a refractory metal having a tensile stress characteristic, (e.g., tungsten). The refractory metal may be formed using a CVD process. The intermediate barrier layer **22** may be disposed on a bottom surface and side surfaces of the intermediate contact plug **24C** and may extend on a bottom surface and side surfaces of the intermediate interconnection **24L**. The intermediate barrier layer **22** located under the intermediate contact plug **24C** may be in contact with the upper surface of the lower interconnection **16L**.

In example embodiments, the intermediate capping layer **27** may cover an upper surface of the intermediate interconnection **24L** of the intermediate interconnection structure **26**.

The upper interconnection structure **48** may include an upper contact plug **42**, an upper interconnection **46**, an upper plug barrier layer **40**, and an upper interconnection barrier layer **44**.

The upper contact plug **42** may pass through the third lower interlayer insulating layer LILD3. The upper plug barrier layer **40** may cover a bottom surface and side surfaces of the upper contact plug **42**. The upper plug barrier layer **40** located under the upper contact plug **42** may be in contact with the upper surface of the intermediate interconnection **24L**. The upper plug barrier layer **40** may be formed of a conductive nitride (e.g., TiN). The upper contact plug **42** may be formed of a refractory metal having a tensile stress characteristic (e.g., tungsten). The refractory metal may be formed using a CVD process.

The upper interconnection **46** may be disposed on the third lower interlayer insulating layer **LILD3** and may overlap the upper contact plug **42**. The upper interconnection barrier layer **44** may be disposed under a bottom surface of the upper interconnection **46** and may not cover side surfaces of the upper interconnection **46**. The upper interconnection barrier layer **44** may be disposed under the bottom surface of the upper interconnection **46** and may not extend on the side surfaces of the upper interconnection **46**.

The upper interconnection barrier layer **44** may be formed of a conductive nitride, for example, **TiN**. The upper interconnection **46** may be formed of a refractory metal having a different stress characteristic from the lower and intermediate interconnections **16L** and **24L** having a tensile stress characteristic. For example, the upper interconnection **46** may be formed of tungsten, which may be formed by a physical vapor deposition (PVD) process capable of adjusting the stress.

The upper contact plug **42** and the upper interconnection **46** may be spaced apart from each other, and the upper interconnection barrier layer **44** may be interposed between the upper contact plug **42** and the upper interconnection **46**.

In example embodiments, the upper capping layer **49** may cover an upper surface and the side surfaces of the upper interconnection **46** of the upper interconnection structure **48**. Therefore, the bottom surface of the upper interconnection **46** may be covered by the upper interconnection barrier layer **44** capable of being formed of a conductive nitride (e.g., **TiN**), and the upper surface and the side surfaces of the upper interconnection **46** may be covered by the upper capping layer **49** capable of being formed of an insulating nitride (e.g., **SiN**).

A thickness **Ta1** of the upper interconnection **46** may be greater than a thickness **Ta2** of the intermediate interconnection **24L** and a thickness **Ta3** of the lower interconnection **16L**. The thickness **Ta2** of the intermediate interconnection **24L** may be greater than the thickness **Ta3** of the lower interconnection **16L**.

An angle $\theta a1$ between the upper surface of the upper interconnection **46** and the side surface thereof may be greater than an angle $\theta a2$ between the upper surface of the intermediate interconnection **24L** and the side surface thereof and an angle $\theta a3$ between the upper surface of the lower interconnection **16L** and the side surface thereof. The angle $\theta a1$ between the upper surface of the upper interconnection **46** and the side surface thereof may be an obtuse angle, and the angle $\theta a2$ between the upper surface of the intermediate interconnection **24L** and the side surface thereof and the angle $\theta a3$ between the upper surface of the lower interconnection **16L** and the side surface thereof may be acute angles.

The side surfaces of the upper interconnection **46** may be positive slopes. The side surfaces of the lower and intermediate interconnections **16L** and **24L** may be negative slopes.

A stress adjustment pattern **48d**, which may be formed of the same material and on the same plane as the upper interconnection **46**, may be disposed on the third lower interlayer insulating layer **LILD3**. The stress adjustment pattern **48d** may limit (and/or suppress) the warpage of the semiconductor substrate **2**.

In example embodiments, the fourth lower interlayer insulating layer **LILD4** may be disposed on the third lower interlayer insulating layer **LILD3** and may cover the upper interconnection structure **48**.

In example embodiments, the upper capping layer **49** may be disposed between the third and fourth lower interlayer

insulating layers **LILD3** and **LILD4** and may cover the upper surface and the side surfaces of the upper interconnection **46**.

Referring to FIGS. **1** and **3**, a semiconductor pattern **52** may be disposed on the lower interlayer insulating layer **LILD**. The semiconductor pattern **52** may be formed of a silicon material. For example, the semiconductor pattern **52** may be formed of polysilicon. The semiconductor pattern **52** may be doped with impurities. For example, the semiconductor pattern **52** may be formed to be a P-type conductivity type.

An intermediate interlayer insulating layer **MILD** may be disposed on side surfaces of the semiconductor pattern **52**. The intermediate interlayer insulating layer **MILD** may be formed of silicon oxide.

A three-dimensional memory array including a plurality of memory cells may be disposed on the semiconductor pattern **52**. The three-dimensional memory array may include a plurality of memory strings perpendicular to the semiconductor pattern **52**. Each of the plurality of memory cells may include a charge trap layer. The three-dimensional memory array may include a plurality of cell gates **CG** and a plurality of cell vertical structures **CV**.

The plurality of cell gates **CG** may be disposed on the semiconductor pattern **52**. The cell gates **CG** may be spaced apart from each other in a vertical direction **Z**. Edges of the cell gates **CG** may be arranged in a step structure which descends stepwise from top to bottom. Cell interlayer insulating layers **CILD** each may be disposed under each of the cell gates **CG**. The cell interlayer insulating layers **CILD** may be formed of silicon oxide.

Each of the cell gates **CG** may include a cell gate conductive pattern **72** and a second cell dielectric **70**. The second cell dielectric **70** may be disposed on an upper surface, lower surface, and side surfaces of the cell gate conductive pattern **72**. The cell gate conductive pattern **72** may include a cell barrier layer **71a** and a cell interconnection **71b**. The cell barrier layer **71a** may be disposed to surround the cell interconnection **71b**. The cell barrier layer **71a** may be formed of a conductive metal nitride.

The cell interconnections **71b** of the cell gate conductive patterns **72** may include a tungsten material. For example, the cell interconnections **71b** of the cell gate conductive patterns **72** may be formed of a refractory metal having a tensile stress characteristic, for example, tungsten formed using a CVD process.

A lowermost cell gate conductive pattern among the cell gate conductive patterns **72** may be a gate electrode of a ground select transistor, and an uppermost cell gate conductive pattern may be a gate electrode of a string select transistor. A plurality of patterns disposed in a center among the cell gate conductive patterns **72** may be cell word lines.

The plurality of cell vertical structures **CV** may be disposed on the semiconductor pattern **52** and may pass through the cell gates **CG** and the cell interlayer insulating layers **CILD**.

Each of the plurality of cell vertical structures **CV** may include a semiconductor epitaxial layer **60**, a first cell dielectric **61**, a cell semiconductor layer **62**, a core insulating pattern **63**, and a cell pad pattern **64**. The cell pad pattern **64** may be disposed on the core insulating pattern **63**. The cell semiconductor layer **62** may be disposed on the semiconductor epitaxial layer **60**. The cell semiconductor layer **62** may be disposed on side surfaces and a bottom surface of the core insulating pattern **63**. The first cell dielectric **61** may be disposed on an outer side of the cell semiconductor layer **62**. The cell semiconductor layer **62** and the cell pad pattern **64**

may be formed of silicon. For example, the cell semiconductor layer **62** and the cell pad pattern **64** may be formed of polysilicon.

Any one of the first and second cell dielectrics **61** and **70** may be an element capable of storing data. Any one of the first and second cell dielectrics **61** and **70** may include a charge trap layer. For example, the first cell dielectric **61** may include a tunnel dielectric layer (e.g., silicon oxide) and a data storage layer (e.g., a silicon nitride layer or the like capable of trapping charges), which are sequentially formed on the cell semiconductor layer **62**. The second cell dielectric **70** may include a blocking dielectric. The first and second cell dielectrics **61** and **70** may have the same structure as a dielectric including an data storage layer disposed between a control gate of a NAND flash memory device and a body of a cell transistor of the NAND flash memory device. However, example embodiments of inventive concepts are not limited to the structure of the NAND flash memory device and may be used in various memory devices.

A source pattern **77** may be disposed on the semiconductor pattern **52** to pass through the cell gates CG and the cell interlayer insulating layers CILD and to be spaced apart from the cell vertical structures CV. The source pattern **77** may be formed of a conductive material (e.g., a material such as Ti, TiN, W, or the like). A source impurity region CS having a different conductive type from the semiconductor pattern **52** for example, an N-type conductivity type may be disposed in the semiconductor pattern **52** under the source pattern **77**.

Peripheral bit line contact structures **80a**, **82a**, **84a**, and **86a** may be disposed on the upper interconnection structure **48** of the first peripheral interconnection structure **50a**. The peripheral bit line contact structures **80a**, **82a**, **84a**, and **86a** may include a first peripheral bit line contact structure **80a**, a second peripheral bit line contact structure **82a**, a third peripheral bit line contact structure **84a**, and a fourth peripheral bit line contact structure **86a**, which are sequentially arranged in an upward direction Z.

Peripheral word line contact structures **80b**, **82b**, **84b**, and **86b** may be disposed on the upper interconnection structure **48** of the second peripheral interconnection structure **50b**. The peripheral word line contact structures **80b**, **82b**, **84b**, and **86b** may include a first peripheral word line contact structure **80b**, a second peripheral word line contact structure **82b**, a third peripheral word line contact structure **84b**, and a fourth peripheral word line contact structure **86b**, which are sequentially arranged in the upward direction Z.

Well contact structures **80c**, **82c**, and **84c** may be disposed on the semiconductor pattern **52**. The well contact structures **80c**, **82c**, and **84c** may include a first well contact structure **80c**, a second well contact structure **82c**, and a third well contact structure **84c**, which are sequentially arranged in the upward direction Z.

Cell gate contact structures **80d**, **82d**, **84d**, and **86d** may be disposed on the cell gates CG to be electrically connected to the cell gates CG. The cell gate contact structures **80d**, **82d**, **84d**, and **86d** may include a first cell gate contact structure **80d**, a second cell gate contact structure **82d**, a third cell gate contact structure **84d**, and a fourth cell gate contact structure **86d**, which are sequentially arranged in the upward direction Z.

Cell bit line contact structures **82e**, **84e**, and **86e** may be disposed to be electrically connected to the cell vertical structures CV. The cell bit line contact structures **82e**, **84e**, and **86e** may include a first cell bit line contact structure **82e**, a second cell bit line contact structure **84e**, and a third cell

bit line contact structure **86e**, which are sequentially arranged in the upward direction Z.

A bit line connection structure **88a** may be disposed to electrically connect the cell bit line contact structures **82e**, **84e**, and **86e** to the peripheral bit line contact structures **80a**, **82a**, **84a**, and **86a**. A word line connection structure **88b** may be disposed to electrically connect the cell gate contact structures **80d**, **82d**, **84d**, and **86d** to the peripheral word line contact structures **80b**, **82b**, **84b**, and **86b**.

Each of the first peripheral bit line contact structure **80a**, the first peripheral word line contact structure **80b**, and the first cell gate contact structure **80d** may include a contact plug **78b** and a barrier layer **78a** which covers side surfaces and a bottom surface of the contact plug **78b**.

Each of the second peripheral bit line contact structure **82a**, the second peripheral word line contact structure **82b**, the second well contact structure **82c**, the second cell gate contact structure **82d**, and the first cell bit line contact structure **82e** may include a contact plug **81b** and a barrier layer **81a** which covers side surfaces and a bottom surface of the contact plug **81b**.

Each of the third peripheral bit line contact structure **84a**, the third peripheral word line contact structure **84b**, the third cell gate contact structure **84d**, and the second cell bit line contact structure **84e** may include an intermediate interconnection layer **83b** and a barrier layer **83a** which covers side surfaces and a bottom surface of the intermediate interconnection layer **83b**.

Each of the fourth peripheral bit line contact structure **86a**, the fourth peripheral word line contact structure **86b**, the fourth cell gate contact structure **86d**, and the third cell bit line contact structure **86e** may include a contact plug **85b** and a barrier layer **85a** which covers side surfaces and a bottom surface of the contact plug **85b**.

Each of the bit line connection structure **88a** and the word line connection structure **88b** may include a connection interconnection layer **87b** and a barrier layer **87a** which covers side surfaces and a bottom surface of the connection interconnection layer **87b**.

An upper interlayer insulating layer UILD may be disposed on the semiconductor pattern **52** and the intermediate interlayer insulating layer MILD. The upper interlayer insulating layer UILD may cover the cell gates CG, the cell vertical structures CV, the cell bit line contact structures **82e**, **84e**, and **86e**, the peripheral bit line contact structures **80a**, **82a**, **84a**, and **86a**, the bit line connection structure **88a**, the cell gate contact structures **80d**, **82d**, **84d**, and **86d**, the peripheral word line contact structures **80b**, **82b**, **84b**, and **86b**, and the word line connection structure **88b**.

A metal interconnection **92** may be disposed on the upper interlayer insulating layer UILD. An angle between an upper surface of the metal interconnection **92** and a side surface thereof may be an obtuse angle.

The lower interconnection **16L** or the intermediate interconnection **24L** may be formed of a refractory metal having a tensile stress characteristic, for example, tungsten formed using a CVD process. Further, the cell interconnections **71b** of the cell gate conductive patterns **72** of the cell gates CG may be formed of a refractory metal having a tensile stress characteristic, for example, tungsten formed using a CVD process.

The upper interconnection **46** of the upper interconnection structure **48** may be formed of a metal material having a different stress characteristic from the lower interconnection **16L**, the intermediate interconnection **24L**, and the cell gate conductive patterns **72**. For example, the upper interconnection **46** may be formed to have stress capable of preventing

or minimizing the warpage of the semiconductor substrate **2** in consideration of the warpage of the semiconductor substrate **2** including the lower interconnection **16L**, the intermediate interconnection **24L**, and the cell gate conductive pattern **72**. The upper interconnection **46** may be formed of a refractory metal having a different stress characteristic from the tensile stress of the lower interconnection **16L**, the intermediate interconnection **24L**, and the cell gate conductive patterns **72**, for example, a compressive stress characteristic. For example, the upper interconnection **46** may be formed of a PVD tungsten material formed by adjusting the stress. The PVD tungsten material may be a tungsten material formed using a PVD process.

The upper interconnection **46** of the upper interconnection structure **48** may be formed of a refractory metal formed using a PVD process and the upper contact plug **42** may be formed of a refractory metal formed using a CVD process. However, example embodiments are not limited thereto.

Another example of the upper interconnection structure **48** will be described with reference to FIGS. **4** and **5**.

Referring to FIGS. **4** and **5**, an upper interconnection structure **148** may include an upper contact plug **146C**, an upper interconnection **146L**, and an upper barrier layer **140**. The upper contact plug **146C** and the upper interconnection **146L** may be integrally formed. The upper barrier layer **140** may cover a bottom surface and side surfaces of the upper contact plug **146C** and a bottom surface of the upper interconnection **146L**. The upper barrier layer **140** may not cover side surfaces of the upper interconnection **146L**.

The upper barrier layer **140** may be formed of a conductive metal nitride, for example, TiN. The upper interconnection **146L** and the upper contact plug **146C** may be formed of tungsten, which is formed by a PVD process capable of adjusting the stress.

An angle θ_{a1} between an upper surface of the upper interconnection **146L** and the side surface thereof may be an obtuse angle similar to the upper interconnection **46** in FIGS. **1** and **2**. Further, the upper interconnection **146L** may have a greater thickness T_{a1} than a thickness T_{a2} of an intermediate interconnection **24L** and a thickness T_{a3} of a lower interconnection **16L** similar to the upper interconnection **46** in FIGS. **1** and **2**.

The intermediate interconnection structure **26** and the lower interconnection structure **18** described in FIGS. **1** and **2** and the upper interconnection structure **148** may constitute first and second peripheral interconnection structures **150a** and **150b**.

Next, a modified example of a semiconductor device in accordance with example embodiments of inventive concepts will be described with reference to FIGS. **6A**, **6B**, **7A**, **7B**, and **8**.

FIG. **6A** is a layout showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts. FIG. **6B** is a plan view showing a modified example of a semiconductor device in accordance with example embodiments of inventive concepts. FIG. **7A** is a cross-sectional view showing a region taken along line I-I' of FIG. **6B** and FIG. **7B** is a cross-sectional view showing a region taken along line II-II' of FIG. **6B**. FIG. **8** is an enlarged cross-sectional view showing some components of FIG. **7A**.

Referring to FIGS. **6A**, **6B**, **7A**, **7B**, and **8**, a semiconductor substrate **2** may be provided. The semiconductor substrate **2** may be a semiconductor substrate formed of single crystal silicon. An isolation region **6'** which defines an active region **4'** may be disposed on the semiconductor substrate **2**.

Circuits such as X decoders XDEC, peripheral circuits PERI, page buffers PGBUF, and the like may be disposed on the semiconductor substrate **2**.

A semiconductor pattern **252** may be disposed on the semiconductor substrate **2**. The semiconductor pattern **252** may be formed of silicon. For example, the semiconductor pattern **252** may be formed of polysilicon.

In example embodiments, the peripheral circuit PERI and the page buffer PGBUF may be disposed between the semiconductor pattern **252** and the semiconductor substrate **2**.

In example embodiments, the X decoder XDEC may not overlap the semiconductor pattern **252**. However, example embodiments are not limited thereto. For example, the X decoder XDEC may overlap the semiconductor pattern **252**.

A first peripheral transistor PTR1' and a second peripheral transistor PTR2' may be disposed on the semiconductor substrate **2**. The first peripheral transistor PTR1' may include a first peripheral gate PG1' and a first source/drain region PSD1', and the second peripheral transistor PTR2' may include a second peripheral gate PG2' and a second source/drain region PSD2'.

In example embodiments, the first peripheral transistor PTR1' may be a transistor constituting the peripheral circuit PERI, and the second peripheral transistor PTR2' may be a transistor constituting the X decoder XDEC. The first peripheral transistor PTR1' may overlap the semiconductor pattern **252** and the second peripheral transistor PTR2' may not overlap the semiconductor pattern **252**.

A lower interlayer insulating layer LILD' may be disposed on the semiconductor substrate **2**.

The lower interlayer insulating layer LILD' may be formed with a plurality of layers. For example, the lower interlayer insulating layer LILD' may include a first lower interlayer insulating layer LILD1', a second lower interlayer insulating layer LILD2', a third lower interlayer insulating layer LILD3', a fourth lower interlayer insulating layer LILD4', and a fifth lower interlayer insulating layer LILD5', which are sequentially stacked.

A lower capping layer **219** may be disposed between the first lower interlayer insulating layer LILD1' and the second lower interlayer insulating layer LILD2'. A first intermediate capping layer **227** may be disposed between the second lower interlayer insulating layer LILD2' and the third lower interlayer insulating layer LILD3'. A second intermediate capping layer **237** may be disposed between the third lower interlayer insulating layer LILD3' and the fourth lower interlayer insulating layer LILD4'. An upper capping layer **249** may be disposed between the fourth lower interlayer insulating layer LILD4' and the fifth lower interlayer insulating layer LILD5'.

The lower interlayer insulating layer LILD' may be formed with an oxide-based insulating layer (e.g., a silicon oxide layer or a low dielectric material layer), and the lower, first intermediate, second intermediate, and upper capping layers **219**, **227**, **237**, and **249** may be formed with a nitride-based insulating layer (e.g., a silicon nitride layer).

First and second peripheral interconnection structures **250a** and **250b** may be disposed on the semiconductor substrate **2**. The first and second peripheral interconnection structures **250a** and **250b** may be disposed in the lower interlayer insulating layer LILD'.

The first peripheral interconnection structure **250a** may be electrically connected to the first peripheral transistor PTR1' and the second peripheral interconnection structure **250b** may be electrically connected to the second peripheral transistor PTR2'. For example, the first peripheral intercon-

nection structure **250a** may be electrically connected to the first source/drain region **PSD1'** of the first peripheral transistor **PTR1'**, and the second peripheral interconnection structure **250b** may be electrically connected to the second source/drain region **PSD2'** of the second peripheral transistor **PTR2'**.

Each of the first and second peripheral interconnection structures **250a** and **250b** may include a lower interconnection structure **218**, an intermediate interconnection structure **236** disposed on the lower interconnection structure **218**, and an upper interconnection structure **248** disposed on the intermediate interconnection structure **236**. The intermediate interconnection structure **236** may include a first intermediate interconnection structure **226** and a second intermediate interconnection structure **234** disposed on the first intermediate interconnection structure **226**.

The lower interconnection structure **218** may be a damascene interconnection structure which fills a lower opening **208** in the first lower interlayer insulating layer **LILD1'** with a conductive material. The lower opening **208** may include a lower contact hole **208H** which exposes the first source/drain region **PSD1'** and a lower interconnection trench **208T** disposed on the lower contact hole **208H**.

The lower interconnection structure **218** may include a lower contact plug **216C**, a lower interconnection **216L**, a lower conductive layer **212**, and a lower barrier layer **214**. The lower contact plug **216C**, the lower interconnection **216L**, the lower conductive layer **212**, and the lower barrier layer **214** may correspond to the lower contact plug **16C**, the lower interconnection **16L**, the lower conductive layer **12**, and the lower barrier layer **14** described in FIGS. **1** and **2**, respectively, and may be formed of the same material in the same structure. For example, the lower contact plug **216C** and the lower interconnection **216L** may be integrally formed. Further, the lower contact plug **216C** and the lower interconnection **216L** may be formed of a material having a tensile stress characteristic, for example, tungsten formed using a CVD process.

A metal-silicide layer **210** may be disposed under the lower interconnection structure **218**. The metal-silicide layer **210** may be a material made of a metal material constituting the lower conductive layer **212**, for example, Ti, and an element constituting the semiconductor substrate **2**, for example, Si.

In example embodiments, the lower capping layer **219** may cover an upper surface of the lower interconnection **216L** of the lower interconnection structure **218**.

The intermediate interconnection structure **236** may include the first intermediate interconnection structure **226** and the second intermediate interconnection structure **234**.

The first intermediate interconnection structure **226** may be a damascene interconnection structure which fills a first intermediate opening **220** in the second lower interlayer insulating layer **LILD2'** with a conductive material. The first intermediate opening **220** may include a first intermediate contact hole **220H** which exposes the lower interconnection **216L**, and a first intermediate interconnection trench **220T** disposed on the first intermediate contact hole **220H**.

The first intermediate interconnection structure **226** may include a first intermediate contact plug **224C**, a first intermediate interconnection **224L**, and a first intermediate barrier layer **222**. The first intermediate contact plug **224C** may be disposed in the first intermediate contact hole **220H**, and the first intermediate interconnection **224L** may be disposed in the first intermediate interconnection trench **220T**.

The first intermediate interconnection **224L** may be disposed on the first intermediate contact plug **224C**. The first

intermediate contact plug **224C** and the first intermediate interconnection **224L** may be integrally formed. The first intermediate contact plug **224C** and the first intermediate interconnection **224L** may be formed of a refractory metal. The first intermediate contact plug **224C** and the first intermediate interconnection **224L** may be formed of a material having a tensile stress characteristic, for example, tungsten formed using a CVD process.

The first intermediate barrier layer **222** may be disposed on a bottom surface and side surfaces of the first intermediate contact plug **224C** and may extend on a bottom surface and side surfaces of the first intermediate interconnection **224L**. The first intermediate barrier layer **222** may be formed of a metal nitride.

In example embodiments, the first intermediate capping layer **227** may cover an upper surface of the first intermediate interconnection **224L** of the first intermediate interconnection structure **226**.

The second intermediate interconnection structure **234** may be a damascene interconnection structure which fills a second intermediate opening **228** in the third lower interlayer insulating layer **LILD3'** with a conductive material. The second intermediate opening **228** may include a second intermediate contact hole **228H** which exposes the first intermediate interconnection **224L**, and a second intermediate interconnection trench **228T** disposed on the second intermediate contact hole **228H**.

The second intermediate interconnection structure **234** may include a second intermediate contact plug **232C**, a second intermediate interconnection **232L**, and a second intermediate barrier layer **230**. The second intermediate contact plug **232C** may be disposed in the second intermediate contact hole **228H**, and the second intermediate interconnection **232L** may be disposed in the second intermediate interconnection trench **228T**.

The second intermediate contact plug **232C** and the second intermediate interconnection **232L** may be integrally formed. The second intermediate contact plug **232C** and the second intermediate interconnection **232L** may be formed of a refractory metal. The second intermediate contact plug **232C** and the second intermediate interconnection **232L** may be formed of a material having a tensile stress characteristic, for example, tungsten formed using a CVD process.

The second intermediate barrier layer **230** may be disposed on a bottom surface and side surfaces of the second intermediate contact plug **232C** and may extend on a bottom surface and side surfaces of the second intermediate interconnection **232L**. The second intermediate barrier layer **230** may be formed of a metal nitride.

In example embodiments, the second intermediate capping layer **237** may cover an upper surface of the second intermediate interconnection **232L**.

The upper interconnection structure **248** may include an upper contact plug **242**, an upper interconnection **246**, an upper plug barrier layer **240**, and an upper interconnection barrier layer **244**.

The upper contact plug **242** may pass through the fourth lower interlayer insulating layer **LILD4'**. The upper plug barrier layer **240** may cover a bottom surface and side surfaces of the upper contact plug **242**. The upper plug barrier layer **240** may be formed of a metal nitride. The upper contact plug **242** may be formed of a refractory metal having a tensile stress characteristic, for example, tungsten formed using a CVD process.

The upper interconnection **246** may be disposed on the fourth lower interlayer insulating layer **LILD4'** and may overlap the upper contact plug **242**. The upper interconnec-

tion barrier layer **244** may be disposed under a bottom surface of the upper interconnection **246** and may not be disposed on side surfaces of the upper interconnection **246**. The upper interconnection barrier layer **244** may be disposed under the bottom surface of the upper interconnection **246** and may not extend on the side surfaces of the upper interconnection **246**. The upper interconnection barrier layer **244** may cover the bottom surface of the upper interconnection **246** and may not cover the side surfaces of the upper interconnection **246**. The upper contact plug **242** and the upper interconnection **246** may be spaced apart from each other, and the upper interconnection barrier layer **244** may be interposed between the upper contact plug **242** and the upper interconnection **246**.

The upper interconnection barrier layer **244** may be formed of a metal nitride. The upper interconnection **246** may be formed of a refractory metal having a different stress characteristic from the lower, first intermediate, and second intermediate interconnections **216L**, **224L**, and **232L** having a tensile stress characteristic. For example, the upper interconnection **246** may be formed of tungsten, which is formed by a PVD process capable of adjusting the stress.

In example embodiments, the upper capping layer **249** may cover an upper surface and the side surfaces of the upper interconnection **246** of the upper interconnection structure **248**.

A thickness $Tb1$ of the upper interconnection **246** may be greater than a thickness $Tb3$ of the first intermediate interconnection **224L**, a thickness $Tb2$ of the second intermediate interconnection **232L**, and a thickness $Tb4$ of the lower interconnection **216L**. The thicknesses $Tb2$ and $Tb3$ of the first and second intermediate interconnections **224L** and **232L** may be greater than the thickness $Tb4$ of the lower interconnection **216L**.

An angle $\theta b1$ between the upper surface of the upper interconnection **246** and the side surface thereof may be greater than an angle $\theta b3$ between the upper surface of the first intermediate interconnection **224L** and the side surface thereof, an angle $\theta b2$ between the upper surface of the second intermediate interconnection **232L** and the side surface thereof, and an angle $\theta b4$ between the upper surface of the lower interconnection **216L** and the side surface thereof. The angle $\theta b1$ between the upper surface and the side surface of the upper interconnection **246** may be an obtuse angle, and the angles $\theta b2$ and $\theta b3$ between the upper surfaces of the first and second intermediate interconnections **224L** and **232L** and the side surfaces thereof and the angle $\theta b4$ between the upper surface and the side surface of the lower interconnection **216L** may be acute angles.

In example embodiments, the fifth lower interlayer insulating layer **LILD5'** may be disposed on the fourth lower interlayer insulating layer **LILD4'** and may cover the upper interconnection structure **248**.

In example embodiments, the upper capping layer **249** may be disposed between the fourth and fifth lower interlayer insulating layers **LILD4'** and **LILD5'** and may cover the upper surface and the side surfaces of the upper interconnection **246**.

An intermediate interlayer insulating layer **MILD** may be disposed on side surfaces of the semiconductor pattern **252**.

First and second three-dimensional memory arrays **CA1** and **CA2** may be disposed on the semiconductor pattern **252** to be spaced apart from each other. Each of the first and second three-dimensional memory arrays **CA1** and **CA2** may include a plurality of memory strings perpendicular the semiconductor pattern **252**. Each of the first and second

three-dimensional memory arrays **CA1** and **CA2** may include cell gates **CG** and cell vertical structures **CV**.

In example embodiments, the cell gates **CG** and the cell vertical structures **CV** may be the same as the cell gates **CG** and the cell vertical structures **CV** described in FIG. 3. For example, each of the cell gates **CG** may include the cell gate conductive pattern **72** (shown in FIG. 3) and the second cell dielectric **70** (shown in FIG. 3) described in FIG. 3. Further, each of the cell vertical structures **CV** may include the semiconductor epitaxial layer **60** (shown in FIG. 3), the first cell dielectric **61** (shown in FIG. 3), the cell semiconductor layer **62** (shown in FIG. 3), the core insulating pattern **63** (shown in FIG. 3), and the cell pad pattern **64** (shown in FIG. 3) described in FIG. 3. Each of the first and second three-dimensional memory arrays **CA1** and **CA2** may include three-dimensionally arranged a plurality memory cells. Each of the plurality memory cells may include a charge trap layer.

The cell vertical structures **CV** may be disposed between source patterns **277**, which are spaced apart from each other and parallel to each other. Each of the source patterns **277** may be a line shape which extends in a first direction **X**. Each of the source patterns **277** may include a source conductive layer **275** and a source barrier layer **276** which surrounds side surfaces and a bottom surface of the source conductive layer **275**.

A source impurity region **CS** having a different conductive type from the semiconductor pattern **252** may be disposed in the semiconductor pattern **252** under the source pattern **277**. The semiconductor pattern **252** may be a P-type conductivity type and the source impurity region **CS** may be an N-type conductivity type.

In example embodiments, edges of the cell gates **CG** may be arranged between the source patterns **277** in a step structure which descends stepwise from top to bottom.

Cell interlayer insulating layers **CILD** may be disposed under each of the cell gates **CG**. The cell interlayer insulating layers **CILD** may be formed of silicon oxide.

In example embodiments, cell molding layers **254** may be disposed to extend from ends of the cell gates **CG** disposed in a second direction **Y** perpendicular to the first direction **X** in a horizontal direction. Therefore, the cell gates **CG** may be disposed in a step structure in the first direction **X**, and the cell molding layers **254** may be disposed in a step structure in the second direction **Y**.

The cell interlayer insulating layers **CILD** may be disposed on the semiconductor pattern **252**. The cell interlayer insulating layers **CILD** may be disposed under the cell gates **CG** and may extend under the cell molding layers **254**. The cell interlayer insulating layers **CILD** may be formed of silicon oxide.

Peripheral bit line contact structures **280a**, **282a**, **284a**, and **286a** may be disposed on the upper interconnection structure **248** of the first peripheral interconnection structure **250a**. The peripheral bit line contact structures **280a**, **282a**, **284a**, and **286a** may have the same structure as the peripheral bit line contact structure **80a**, **82a**, **84a**, and **86a** described in FIGS. 1 and 3. For example, each of the peripheral bit line contact structure **280a**, **282a**, **284a**, and **286a** may include contact plugs **278b**, **281b**, **283b**, and **285b** and barrier layers **278a**, **281a**, **283a**, and **285a** which cover side surfaces and bottom surfaces of the contact plugs **278b**, **281b**, **283b**, and **285b**. The contact plugs **278b**, **281b**, **283b**, and **285b** may correspond to the contact plugs **78b**, **81b**, **83b**, and **85b** described in FIGS. 1 and 3 and the barrier layers **278a**, **281a**, **283a**, and **285a** may correspond to the barrier layers **78a**, **81a**, **83a**, and **85a** described in FIGS. 1 and 3.

Peripheral word line contact structures **280b**, **282b**, **284b**, and **286b** may be disposed on the upper interconnection structure **248** of the second peripheral interconnection structure **250b**. The peripheral word line contact structures **280b**, **282b**, **284b**, and **286b** may have the same structure as the peripheral word line contact structures **80b**, **82b**, **84b**, and **86b** described in FIGS. 1 and 3. Each of the peripheral word line contact structures **280b**, **282b**, **284b**, and **286b** may include contact plugs **278b**, **281b**, **283b**, and **285b**, and barrier layers **278a**, **281a**, **283a**, and **285a** which cover side surfaces and bottom surfaces of the contact plugs **278b**, **281b**, **283b**, and **285b**.

Well contact structures **280c**, **282c**, and **284c** having the same structure as the well contact structures **80c**, **82c**, and **84c** described with reference to FIG. 1 may be disposed on the semiconductor pattern **252**.

Cell gate contact structures **280d**, **282d**, **284d**, and **286d** may be disposed on the cell gates CG to be electrically connected to the cell gates CG. The cell gate contact structures **280d**, **282d**, **284d**, and **286d** may have the same structure as the cell gate contact structures **80d**, **82d**, **84d**, and **86d** described in FIGS. 1 and 3.

Cell bit line contact structures **282e**, **284e**, and **286e** may be disposed to be electrically connected to the cell vertical structures CV. The cell bit line contact structures **282e**, **284e**, and **286e** may have the same structure as the cell bit line contact structures **82e**, **84e**, and **86e** described in FIGS. 1 and 3.

A bit line connection structure **288a** may be disposed to electrically connect the cell bit line contact structures **282e**, **284e**, and **286e** to the peripheral bit line contact structures **280a**, **282a**, **284a**, and **286a**. A word line connection structure **288b** may be disposed to electrically connect the cell gate contact structures **280d**, **282d**, **284d**, and **286d** to the peripheral word line contact structures **280b**, **282b**, **284b**, and **286b**. Each of the bit line connection structure **288a** and the word line connection structure **288b** may include a connection interconnection layer **287b** and a barrier layer **287a** which covers a bottom surface and side surfaces of the connection interconnection layer **287b**.

An upper interlayer insulating layer UILD may be disposed on the semiconductor pattern **252** and the intermediate interlayer insulating layer MILD. The upper interlayer insulating layer UILD may cover the cell gates CG, the cell vertical structures CV, the cell bit line contact structures **282e**, **284e**, and **286e**, the peripheral bit line contact structures **280a**, **282a**, **284a**, and **286a**, the bit line connection structure **288a**, the cell gate contact structures **280d**, **282d**, **284d**, and **286d**, the peripheral word line contact structures **280b**, **282b**, **284b**, and **286b**, and the word line connection structure **288b**.

A metal interconnection **292** may be disposed on the upper interlayer insulating layer UILD. The metal interconnection **292** may include a barrier layer **291a** and a metal layer **291b** disposed on the barrier layer **291a**. An angle between an upper surface of the metal interconnection **292** and a side surface thereof may be an obtuse angle.

A contact structure **290** including a contact plug **289b** and a barrier layer **289a** which covers side surfaces and a bottom surface of the contact plug **289b** may be disposed under the metal interconnection **292**.

In example embodiments, at least one or all of the lower interconnection **216L**, the first intermediate interconnection **224L**, and the second intermediate interconnection **232L** may be formed of a refractory metal having a tensile stress characteristic, for example, tungsten formed using a CVD process. The cell gates CG may include a refractory metal

having a tensile stress characteristic, for example, tungsten formed using a CVD process.

The upper interconnection **246** of the upper interconnection structure **248** may be formed of a metal material having a different stress characteristic from the lower interconnection **216L**, the first intermediate interconnection **224L**, the second intermediate interconnection **232L**, and the cell gates CG. For example, the upper interconnection **246** may be formed to have stress capable of limiting (and/or suppressing) the warpage of the semiconductor substrate **2** in consideration of the warpage of the semiconductor substrate **2** including the lower interconnection **216L**, the first intermediate interconnection **224L**, the second intermediate interconnection **232L**, and the cell gates CG. The upper interconnection **246** may be formed of a refractory metal having a different stress characteristic from the tensile stress of the lower interconnection **216L**, the first intermediate interconnection **224L**, the second intermediate interconnection **232L**, and the cell gates CG, for example, a compressive stress characteristic. For example, the upper interconnection **246** may be formed of tungsten, which is formed by a PVD process capable of adjusting the stress.

The upper interconnection **246** of the upper interconnection structure **248** may be formed of a refractory metal formed using a PVD process, and the upper contact plug **242** may be formed of a refractory metal formed using a CVD process. However, example embodiments of inventive concepts are not limited thereto.

Another example of the upper interconnection structure **248** will be described with reference to FIGS. 9A, 9B, and 10.

Referring to FIGS. 9A, 9B, and 10, an upper interconnection structure **348** may include an upper contact plug **346C**, an upper interconnection **346L**, and an upper barrier layer **340**. The upper contact plug **346C** and the upper interconnection **346L** may be integrally formed. The upper barrier layer **340** may cover a bottom surface and side surfaces of the upper contact plug **346C** and a bottom surface of the upper interconnection **346L**. The upper barrier layer **340** may not cover side surfaces of the upper interconnection **346L**.

The lower interconnection structure **218** and the intermediate interconnection structure **236** described in FIGS. 7A, 7B, and 8 and the upper interconnection structure **348** may constitute first and second peripheral interconnection structures **350a** and **350b**.

An angle θ_{b1} between an upper surface of the upper interconnection **346L** and a side surface thereof may be an obtuse angle similar to the upper interconnection **246** described in FIGS. 7A, 7B, and 8. Further, the upper interconnection **346L** may have a greater thickness T_{b1} than the thicknesses T_{b2} and T_{b3} of the first and second intermediate interconnections **224L** and **232L** and the thickness T_{b4} of the lower interconnection **216L** similar to the upper interconnection **246** described in FIGS. 7A, 7B, and 8.

Next, a method of forming a semiconductor device in accordance with example embodiments of inventive concepts will be described with reference to FIGS. 6A, 6B, and 11A to 20B. FIGS. 11A to 20B are cross-sectional views showing an example of a method of forming a semiconductor device in accordance with example embodiments of inventive concepts. FIGS. 11A, 12A, 13A, 14A, 15A, 16A, 17A, 18A, 19A, and 20A are cross-sectional views showing regions taken along line I-I' of FIGS. 6B, and 11B, 12B, 13B, 14B, 15B, 16B, 17B, 18B, 19B, and 20B are cross-sectional views showing regions taken along line II-II' of FIG. 6B.

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Referring to FIGS. 6A, 6B, 11A, and 11B, a semiconductor substrate **2** may be provided. The semiconductor substrate **2** may be a single crystal silicon substrate. An isolation region **6'** which defines an active region **4'** may be formed on the semiconductor substrate **2**.

Individual elements constituting circuits may be formed on the semiconductor substrate **2**. The circuits may be X decoders XDEC, peripheral circuits PERI, and page buffers PGBUF.

The individual elements constituting the circuits may include a first peripheral transistor PTR1' and a second peripheral transistor PTR2'. The first peripheral transistor PTR1' may include a first peripheral gate PG1' and a first source/drain region PSD1', and the second peripheral transistor PTR2' may include a second peripheral gate PG2' and a second source/drain region PSD2'.

In example embodiments, the first peripheral transistor PTR1' may be a transistor constituting the peripheral circuit PERI, and the second peripheral transistor PTR2' may be a transistor constituting the X decoder XDEC.

A first lower interlayer insulating layer LILD1' may be formed on the semiconductor substrate **2** having the first and second peripheral transistors PTR1' and PTR2'. The first lower interlayer insulating layer LILD1' may be formed of an insulating material such as a silicon oxide-based insulating material.

A lower opening **208** including a lower contact hole **208H** passing through the first lower interlayer insulating layer LILD1' and a lower interconnection trench **208T** crossing an upper portion of the lower contact hole **208H** may be formed using a dual damascene process.

A conductive layer **211** and a barrier layer **213** may be sequentially formed on the semiconductor substrate **2** having the lower opening **208**. The conductive layer **211** may be formed of a metal material, for example, Ti, and the barrier layer **213** may be formed of a metal nitride, for example, TiN. By performing a thermal treatment process, a metal-silicide layer **210** may be formed by reaction of the conductive layer **211** and the semiconductor substrate **2**. The metal-silicide layer **210** may be formed on the source/drain regions PSD1' and PSD2'. An interconnection material layer **215** may be formed on the barrier layer **213**. The interconnection material layer **215** may be formed of a refractory metal having a tensile stress characteristic (e.g., tungsten) and may be formed using a CVD process.

Referring to FIGS. 6A, 6B, 12A, and 12B, a lower interconnection structure **218** may be formed to be defined in the lower opening **208** by planarizing the interconnection material layer **215**, the barrier layer **213**, and the conductive layer **211** until an upper surface of the first lower interlayer insulating layer LILD1' is exposed. The lower interconnection structure **218** may include a lower conductive layer **212** formed by planarizing the conductive layer **211**, a lower barrier layer **214** formed by planarizing the barrier layer **213**, and a lower interconnection **216L** and a lower contact plug **216C** formed by planarizing the interconnection material layer **215**.

A lower capping layer **219** may be formed to cover the lower interconnection structure **218** and the first lower interlayer insulating layer LILD1'. The lower capping layer **219** may be formed of silicon nitride.

Referring to FIGS. 6A, 6B, 13A, and 13B, a second lower interlayer insulating layer LILD2' may be formed on the lower capping layer **219**. A first intermediate opening **220** including a first intermediate contact hole **220H**, which passes through the second lower interlayer insulating layer LILD2' and the lower capping layer **219** and exposes the

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lower interconnection structure **218**, and a first intermediate interconnection trench **220T** crossing an upper portion of the first intermediate contact hole **220H** may be formed using a dual damascene process.

A barrier layer and an interconnection material layer may be sequentially deposited on the substrate having the first intermediate opening **220**, and a first intermediate interconnection structure **226** may be formed by planarizing the interconnection material layer and the barrier layer until an upper surface of the second lower interlayer insulating layer LILD2' is exposed. The first intermediate interconnection structure **226** may include the first intermediate contact plug **224C** (shown in FIG. 8), the first intermediate interconnection **224L** (shown in FIG. 8) which is integrally formed with the first intermediate contact plug **224C** (shown in FIG. 8), and the first intermediate barrier layer **222** (shown in FIG. 8) which covers the bottom surface and the side surfaces of the first intermediate contact plug **224C** (shown in FIG. 8) and the bottom surface and the side surfaces of the first intermediate interconnection **224L** (shown in FIG. 8).

A first intermediate capping layer **227** may be formed to cover the first intermediate interconnection structure **226** and the second lower interlayer insulating layer LILD2'. The first intermediate capping layer **227** may be formed of silicon nitride.

A third lower interlayer insulating layer LILD3' may be formed on the first intermediate capping layer **227**. A second intermediate opening **228** including a second intermediate contact hole **228H**, which passes through the third lower interlayer insulating layer LILD3' and the first intermediate capping layer **227** and exposes the first intermediate interconnection structure **226**, and a second intermediate interconnection trench **228T** crossing an upper portion of the second intermediate contact hole **228H** may be formed using a dual damascene process.

A barrier layer and an interconnection material layer may be sequentially deposited on the substrate having the second intermediate opening **228**, and a second intermediate interconnection structure **234** may be formed by planarizing the interconnection material layer and the barrier layer until an upper surface of the third lower interlayer insulating layer LILD3' is exposed. The second intermediate interconnection structure **234** may include a second intermediate contact plug **232C** (shown in FIG. 8), a first intermediate interconnection **232L** (shown in FIG. 8) which is integrally formed with the second intermediate contact plug **232C** (shown in FIG. 8), and a second intermediate barrier layer **230** (shown in FIG. 8) which covers the bottom surface and the side surfaces of the second intermediate contact plug **232C** (shown in FIG. 8) and the bottom surface and the side surfaces of the second intermediate interconnection **232L** (shown in FIG. 8).

A second intermediate capping layer **237** may be formed to cover the second intermediate interconnection structure **234** and the third lower interlayer insulating layer LILD3'. The second intermediate capping layer **237** may be formed of silicon nitride.

Referring to FIGS. 6A, 6B, 14A, and 14B, a fourth lower interlayer insulating layer LILD4' may be formed on the second intermediate capping layer **237**.

An upper contact hole **238** may be formed to pass through the fourth lower interlayer insulating layer LILD4' and the second intermediate capping layer **237**. A barrier layer and an interconnection material layer may be formed on the substrate having the upper contact hole **238**, and an upper plug barrier layer **240** and an upper contact plug **242** may be formed by planarizing the interconnection material layer and

the barrier layer until an upper surface of the fourth lower interlayer insulating layer LILD4' is exposed.

Referring to FIGS. 6A, 6B, 15A, and 15B, a barrier material layer 243 and an upper interconnection material layer 245 may be formed on the semiconductor substrate having the upper plug barrier layer 240 and the upper contact plug 242. The barrier material layer 243 may be formed of a metal nitride such as TiN, etc.

The upper interconnection material layer 245 may be formed of a material having a different stress characteristic from the lower interconnection 216L and the first and second intermediate interconnections 224L and 232L. For example, the lower interconnection 216L and the first and second intermediate interconnections 224L and 232L may be formed of a refractory metal formed by performing a CVD process, for example, CVD tungsten and thus may have tensile stress, and the upper interconnection material layer 245 may be formed of a refractory metal formed by performing a PVD process, for example, PVD tungsten. The stress of PVD tungsten may be adjusted according to a PVD process condition. For example, the PVD tungsten may have compressive stress.

Referring to FIGS. 6A, 6B, 16A, and 16B, an upper barrier layer 244 and an upper interconnection 246 which are sequentially stacked may be formed by patterning the upper interconnection material layer 245 and the barrier material layer 243.

An upper capping layer 249 may be formed to cover the upper barrier layer 244 and the upper interconnection 246. The upper capping layer 249 may be formed of silicon nitride.

Referring to FIGS. 6A, 6B, 17A, and 17B, a fifth lower interlayer insulating layer LILD5' may be formed on the upper capping layer 249. The fifth lower interlayer insulating layer LILD5' may be formed of silicon oxide. A semiconductor pattern 252 may be formed on the fifth lower interlayer insulating layer LILD5'. The semiconductor pattern 252 may be formed of polysilicon having a P-type conductivity type.

Referring to FIGS. 6A, 6B, 18A, and 18B, an insulating layer may be formed on the semiconductor substrate having the semiconductor pattern 252, and an intermediate interlayer insulating layer MILD may be formed by planarizing the insulating layer until an upper surface of the semiconductor pattern 252 is exposed.

Cell interlayer insulating layers CILD and molding layers 254 may be alternately and repeatedly formed on the semiconductor pattern 252. The cell interlayer insulating layers CILD may have an etch selectivity with respect to the molding layers 254. For example, the cell interlayer insulating layers CILD may be formed of silicon oxide, and the molding layers 254 may be formed of silicon nitride. The cell interlayer insulating layers CILD and the molding layers 254 may be patterned and edges thereof may be formed in a step structure.

An insulating layer may be formed on the substrate having the cell interlayer insulating layers CILD and the molding layers 254, and a first upper interlayer insulating layer UILD1 may be formed by planarizing the insulating layer. A second upper interlayer insulating layer UILD2 may be formed on the cell interlayer insulating layers CILD, the molding layers 254, and the first upper interlayer insulating layer UILD1.

A plurality of cell structures CV may be formed to pass through the second upper interlayer insulating layer UILD2,

the cell interlayer insulating layers CILD, and the molding layers 254 and to be connected to the semiconductor pattern 252.

The formation of the cell vertical structures CV may include forming holes passing through the second upper interlayer insulating layer UILD2, the cell interlayer insulating layers CILD, and the molding layers 254, forming the semiconductor epitaxial layer 60 (shown in FIG. 3) on the semiconductor pattern 252 exposed by the holes, conformally forming the first cell dielectric 61 (shown in FIG. 3) on side walls of the holes, conformally forming the semiconductor layer 62 (shown in FIG. 3) on the first cell dielectric 61 (shown in FIG. 3), forming the core insulating pattern 63 (shown in FIG. 3), which partially fills the holes, on the semiconductor layer 62 (shown in FIG. 3), and forming the cell pad pattern 64 (shown in FIG. 3) on the core insulating pattern 63 (shown in FIG. 3).

Referring to FIGS. 6A, 6B, 19A, and 19B, a third upper interlayer insulating layer UILD3 may be formed to cover the cell vertical structures CV and the second upper interlayer insulating layer UILD2.

Trenches 266 may be formed to pass through the third upper interlayer insulating layer UILD3, the second upper interlayer insulating layer UILD2, the cell interlayer insulating layers CILD, and the molding layers 254. Empty spaces may be formed by removing the molding layers 254 adjacent to the trenches 266, and cell gates CG may be formed in the empty spaces. The cell gates CG may be formed to surround side surfaces of the cell vertical structures CV.

An insulating spacer 274 may be formed on side walls of the trenches 266. A source impurity region CS having a different conductive type from the semiconductor pattern 252, for example, an N-type conductivity type, may be formed in the semiconductor pattern 252 under the trenches 266. Source patterns 277 may be formed to fill the trenches 266. Each of the source patterns 277 may include a source conductive layer 276, and a source barrier layer 275 which surrounds side surfaces and a bottom surface of the source conductive layer 276. The source conductive layer 276 may be formed of a refractory metal formed using a CVD process.

Referring to FIGS. 6A, 6B, 20A, and 20B, a fourth upper interlayer insulating layer UILD4 may be formed on the third upper interlayer insulating layer UILD3. A first peripheral bit line contact structure 280a, a first peripheral word line contact structure 280b, a first well contact structure 280c, and a first cell gate contact structure 280d may be formed.

Each of the first peripheral bit line contact structure 280a, the first peripheral word line contact structure 280b, the first well contact structure 280c, and the first cell gate contact structure 280d may include a contact plug 278b and a barrier layer 278a which covers a bottom surface and side surfaces of the contact plug 278b.

The first peripheral bit line contact structure 280a may pass through the first to fourth upper interlayer insulating layers UILD1 to UILD4, the intermediate interlayer insulating layer MILD, and the fifth lower interlayer insulating layer LILD5' and may be formed on an upper interconnection structure 248 of the first peripheral interconnection structure 250a.

The first peripheral word line contact structure 280b may pass through the first to fourth upper interlayer insulating layers UILD1 to UILD4, the intermediate interlayer insulating layer MILD, and the fifth lower interlayer insulating

layer LILD5' and may be formed on the upper interconnection structure 248 of the second peripheral interconnection structure 250b.

The first well contact structure 280c may pass through the first to fourth upper interlayer insulating layers UILD1 to UILD4 and may be formed on the semiconductor pattern 252, and the first cell gate contact structure 280d may pass through the first to fourth upper interlayer insulating layers UILD1 to UILD4 and may be formed on the edges of the cell gates CG.

A fifth upper interlayer insulating layer UILD5 may be formed on the fourth upper interlayer insulating layer UILD4. A second peripheral bit line contact structure 282a, a second peripheral word line contact structure 282b, a second well contact structure 282c, a second cell gate contact structure 282d, and a first cell bit line contact structure 282e may be formed. The second peripheral bit line contact structure 282a may be formed on the first peripheral bit line contact structure 280a and may pass through the fifth upper interlayer insulating layer UILD5.

The second peripheral word line contact structure 282b may be formed on the first peripheral word line contact structure 280b and may pass through the fifth upper interlayer insulating layer UILD5. The second well contact structure 282c may be formed on the first well contact structure 280c and may pass through the fifth upper interlayer insulating layer UILD5. The second cell gate contact structure 282d may be formed on the first cell gate contact structure 280d and may pass through the fifth upper interlayer insulating layer UILD5. The first cell bit line contact structure 282e may be formed on the cell vertical structure CV and may pass through the third to fifth upper interlayer insulating layers UILD3 to UILD5.

Each of the second peripheral bit line contact structure 282a, the second peripheral word line contact structure 282b, the second well contact structure 282c, the second cell gate contact structure 282d, and the first cell bit line contact structure 282e may include a contact plug 281b and a barrier layer 281a which covers side surfaces and a bottom surface of the contact plug 281b.

A sixth upper interlayer insulating layer UILD6 may be formed on the fifth upper interlayer insulating layer UILD5. A third peripheral bit line contact structure 284a disposed on the second peripheral bit line contact structure 282a, a third peripheral word line contact structure 284b disposed on the second peripheral word line contact structure 282b, a third cell gate contact structure 284d disposed on the second cell gate contact structure 282d, and a second cell bit line contact structure 284e disposed on the first cell bit line contact structure 282e may be formed to pass through the sixth upper interlayer insulating layer UILD6.

Each of the third peripheral bit line contact structure 284a, the third peripheral word line contact structure 284b, the third cell gate contact structure 284d, and the second cell bit line contact structure 284e may include an intermediate interconnection 283b and a barrier layer 283a which covers side surfaces and a bottom surface of the intermediate interconnection 283b.

A seventh upper interlayer insulating layer UILD7 may be formed on the sixth upper interlayer insulating layer UILD6. A fourth peripheral bit line contact structure 286a disposed on the third peripheral bit line contact structure 284a, a fourth peripheral word line contact structure 286b disposed on the third peripheral word line contact structure 284b, a fourth cell gate contact structure 286d disposed on the third cell gate contact structure 284d, and a third cell bit line contact structure 286e disposed on the second cell bit line

contact structure 284e may be formed to pass through the seventh upper interlayer insulating layer UILD7.

Each of the fourth peripheral bit line contact structure 286a, the fourth peripheral word line contact structure 286b, the fourth cell gate contact structure 286d, and the third cell bit line contact structure 286e may include a contact plug 285b and a barrier layer 285a which covers side surfaces and a bottom surface of the contact plug 285b.

An eighth upper interlayer insulating layer UILD8 may be formed on the seventh upper interlayer insulating layer UILD7. A bit line connection structure 288a and a word line connection structure 288b may be formed to pass through the eighth upper interlayer insulating layer UILD8. The bit line connection structure 288a may be electrically connected to the fourth peripheral bit line contact structure 286a and the third cell bit line contact structure 286e. The word line connection structure 288b may be electrically connected to the fourth peripheral word line contact structure 286b and the fourth cell gate contact structure 286d.

A ninth upper interlayer insulating layer UILD9 may be formed on the eighth upper interlayer insulating layer UILD8.

A contact structure 290 may be formed to pass through the ninth upper interlayer insulating layer UILD9. The contact structure 290 may include a contact plug 289b and a barrier layer 289a which covers a bottom surface and side surfaces of the contact plug 289b.

Referring again to FIGS. 6A, 6B, 7A, and 7B, a metal interconnection 292 may be formed on the ninth upper interlayer insulating layer UILD9. The metal interconnection 292 may include a barrier layer 291a and a metal layer 291b disposed on the barrier layer 291a. An angle between an upper surface of the metal interconnection 292 and a side surface thereof may be an obtuse angle.

Next, a modified example of a method of forming a semiconductor device in accordance with example embodiments of inventive concepts will be described with reference to FIGS. 6A, 6B, 21A, and 21B. FIGS. 21A to 22B are cross-sectional views showing a modified example of a method of forming a semiconductor device in accordance with example embodiments of inventive concepts. FIGS. 21A and 22A are cross-sectional views showing regions taken along line I-I' of FIG. 6B, and FIGS. 21B and 22B are cross-sectional views showing regions taken along line II-II' of FIG. 6B.

Referring to FIGS. 6A, 6B, 21A, and 21B, the same first and second peripheral transistors PTR1' and PTR2', first lower interlayer insulating layer LILD1', lower interconnection structure 218, and lower capping layer 219 as described in FIGS. 11A to 12B may be sequentially formed on the semiconductor substrate 2. The same second lower interlayer insulating layer LILD2', first intermediate interconnection structure 226, first intermediate capping layer 227, third lower interlayer insulating layer LILD3', second intermediate interconnection structure 234, and second intermediate capping layer 237 as described in FIGS. 13A and 13B may be sequentially formed.

A fourth lower interlayer insulating layer LILD4' may be formed on the second intermediate capping layer 237. An upper contact hole 238 may be formed to pass through the fourth lower interlayer insulating layer LILD4' and the second intermediate capping layer 237.

A barrier material layer 339 and an interconnection material layer 345 may be sequentially formed on the substrate having the upper contact hole 238. The barrier material layer 339 may be formed of a metal nitride. The interconnection

material layer **345** may be formed of a refractory metal (e.g., a tungsten material) and may be formed using a PVD process.

Referring to FIGS. **22A**, and **22B**, an upper interconnection structure **348** may be formed by patterning the barrier material layer **339** and the interconnection material layer **345**.

The upper interconnection structure **348** may include an upper contact plug **346C** formed in the upper contact hole **238**, an upper interconnection **346L** formed on the fourth lower interlayer insulating layer LILD4', and an upper barrier layer **340** which covers a bottom surface and side surfaces of the upper contact plug **346C** and a bottom surface of the upper interconnection **346L**. The upper contact plug **346C** and the upper interconnection **346L** may be integrally formed. The upper barrier layer **340** may not cover side surfaces of the upper interconnection **346L**.

Then, an upper capping layer **249** may be formed to cover the upper interconnection structure **348** and the fourth lower interlayer insulating layer LILD4'. Therefore, the first peripheral interconnection structure **350a** as described in FIG. **10** may be formed.

Then, the same process as described in FIGS. **17A** to **20B** may be performed.

FIG. **23** is a schematic view showing a semiconductor module **400** according to example embodiments of inventive concepts.

Referring to FIG. **23**, the semiconductor module **400** may include memory devices **430** formed on a module substrate **410**. The semiconductor module **400** may include a semiconductor device **420** mounted on the module substrate **410**.

The memory device **430** may include one of the above-described semiconductor devices formed according to example embodiments of inventive concepts. Input/output terminals **440** may be disposed on at least one side of the module substrate **410**.

FIG. **24** is a conceptual block diagram showing an electronic system **500** according to example embodiments of inventive concepts.

Referring to FIG. **24**, in example embodiments of inventive concepts, the electronic system **500** including the semiconductor device formed according to may be provided.

The electronic system **500** may include a body **510**. The body **510** may include a microprocessor unit **520**, a power supply **530**, a function unit **540**, and/or a display controller unit **550**. The body **510** may be a system board or a mother board including a printed circuit board (PCB), etc.

The microprocessor unit **520**, the power supply **530**, the function unit **540**, and the display controller unit **550** may be installed or mounted on the body **510**. A display unit **560** may be disposed on an upper surface of the body **510** or outside the body **510**. For example, the display unit **560** may be disposed on a surface of the body **510**, and then may display an image processed by the display controller unit **550**. The power supply **530** may receive a constant voltage from an external power supply, divide the voltage into various voltages levels, and supply those voltages to the microprocessor unit **520**, the function unit **540**, and the display controller unit **550**, etc. The microprocessor unit **520** may receive a voltage from the power supply **530** to control the function unit **540** and the display unit **560**.

The function unit **540** may perform various functions of the electronic system **500**. For example, when the electronic system **500** is a mobile electronic product such as a cellular phone, etc., the function unit **540** may include various components which perform wireless communication functions such as dialing, image output to the display unit **560**,

or voice output to a speaker through communication with an external apparatus **570**, and when a camera is included, the function unit **540** may serve as an image processor.

In example embodiments, when the electronic system **500** is connected to a memory card to expand the capacity, the function unit **540** may be a memory card controller. The function unit **540** may exchange signals with the external apparatus **570** through a wired or wireless communication unit **580**.

Further, when the electronic system **500** requires a Universal Serial Bus (USB) to expand the functions, the function unit **540** may serve as an interface controller.

FIG. **25** is a schematic block diagram showing an electronic system **600** according to example embodiments of inventive concepts.

Referring to FIG. **25**, the electronic system **600** may include the semiconductor device formed according to example embodiments of inventive concepts. The electronic system **600** may include a memory **612**, a microprocessor **614**, a RAM **616**, and a user interface **618** which perform data communication using a bus **620**. The microprocessor **614** may program and control the electronic system **600**. The RAM **616** may be used as an operational memory of the microprocessor **614**. The microprocessor **614**, the RAM **616** and/or other components may be assembled within a single package. The memory **612** may include the semiconductor device according to example embodiments of inventive concepts.

The user interface **618** may be used to input data to the electronic system **600** or output data from the electronic system **600**. The memory **612** may store operational codes of the microprocessor **614**, data processed by the microprocessor **614**, or data received from the outside. The memory **612** may include a controller and a memory.

According to example embodiments of inventive concepts, in order to increase the degree of integration, a semiconductor pattern may be disposed on a semiconductor substrate, a three-dimensional memory array including three-dimensional memory cells may be disposed on the semiconductor pattern, and a peripheral interconnection structure may be disposed between the semiconductor substrate and the semiconductor pattern. The peripheral interconnection structure may include a lower interconnection structure having a damascene structure capable of forming a fine pattern and an upper interconnection structure capable of improving an electrical characteristic.

Cell gates of the three-dimensional memory array and a lower interconnection of the lower interconnection structure may be formed of a refractory metal formed using a CVD process. The cell gates of the three-dimensional memory array and the lower interconnection of the lower interconnection structure may have a tensile stress characteristic.

In order to limit (and/or suppress) the warpage due to the tensile stress characteristic of the cell gates of the three-dimensional memory array and the lower interconnection of the lower interconnection structure, the upper interconnection may be formed of a refractory metal having a different stress characteristic from the cell gates of the three-dimensional memory array and the lower interconnection of the lower interconnection structure. For example, the upper interconnection may be formed of a metal material, for example, a refractory metal formed using a PVD process capable of adjusting the stress.

It should be understood that example embodiments described herein should be considered in a descriptive sense only and not for purposes of limitation. Descriptions of features or aspects within each device or method according

to example embodiments should typically be considered as available for other similar features or aspects in other devices or methods according to example embodiments. While some example embodiments have been particularly shown and described, it will be understood by one of ordinary skill in the art that variations in form and detail may be made therein without departing from the spirit and scope of the claims.

What is claimed is:

1. A semiconductor device comprising:
a semiconductor substrate;
a semiconductor pattern on the semiconductor substrate;
a three-dimensional memory array on the semiconductor pattern; and
a peripheral interconnection structure between the semiconductor pattern and the semiconductor substrate, the peripheral interconnection structure including a lower interconnection structure, the lower interconnection structure including a lower interconnection, wherein side surfaces of the lower interconnection have negative slopes.

2. The semiconductor device of claim **1**, wherein an angle between an upper surface of the lower interconnection and each of the side surfaces of the lower interconnection is an acute angle.

3. The semiconductor device of claim **1**, wherein the peripheral interconnection structure includes an upper interconnection structure over the lower interconnection structure, the upper interconnection structure including an upper interconnection, and wherein side surfaces of the upper interconnection have positive slopes.

4. The semiconductor device of claim **3**, wherein an angle between an upper surface of the upper interconnection and each of the side surfaces of the upper interconnection is an obtuse angle.

5. The semiconductor device of claim **3**, wherein a thickness of the upper interconnection is greater than a thickness of the lower interconnection.

6. The semiconductor device of claim **3**, wherein the lower interconnection includes a refractory metal having a tensile stress characteristic, and the upper interconnection includes a refractory metal having a different stress characteristic from the lower interconnection.

7. The semiconductor device of claim **3**, wherein the upper interconnection structure further includes an upper barrier layer, and wherein the upper barrier layer is under a bottom surface of the upper interconnection, and does not cover the side surfaces of the upper interconnection.

8. The semiconductor device of claim **1**, wherein the lower interconnection structure further includes a lower contact plug under the lower interconnection, and the lower contact plug is integrally formed with the lower interconnection.

9. The semiconductor device of claim **8**, wherein the lower interconnection structure further includes a lower barrier layer, and wherein the lower barrier layer is under a bottom surface of the lower interconnection, covers the side surfaces of the lower interconnection, and extends on side surfaces and a bottom surface of the lower contact plug.

10. The semiconductor device of claim **1**, wherein the three-dimensional memory array includes a plurality of cell gates disposed on the semiconductor pattern and spaced apart from each other in a direction perpendicular to an upper surface of the semiconductor pattern, and

wherein each of the plurality of cell gates includes a cell gate conductive pattern including a cell interconnection, and the cell interconnection includes a tungsten material.

11. The semiconductor device of claim **10**, wherein the peripheral interconnection structure includes an upper interconnection structure between the lower interconnection structure and the semiconductor pattern, the upper interconnection structure including an upper interconnection, and wherein side surfaces of the upper interconnection have positive slopes.

12. The semiconductor device of claim **11**, wherein the cell interconnection includes a refractory metal having a tensile stress characteristic, and the upper interconnection includes a refractory metal having a different stress characteristic from the cell interconnection.

13. The semiconductor device of claim **10**, further comprising:
a metal interconnection over the three-dimensional memory array, wherein side surfaces of the metal interconnection have positive slopes.

14. The semiconductor device of claim **13**, wherein an angle between an upper surface of the metal interconnection and each of the side surfaces of the metal interconnection is an obtuse angle.

15. The semiconductor device of claim **1**, wherein the peripheral interconnection structure further includes an upper interconnection structure over the lower interconnection structure, the upper interconnection structure including an upper interconnection.

16. The semiconductor device of claim **15**, wherein side surfaces of the upper interconnection have positive slopes.

17. The semiconductor device of claim **15**, wherein a thickness of the upper interconnection is greater than a thickness of the lower interconnection.

18. The semiconductor device of claim **15**, wherein the lower interconnection includes a refractory metal having a tensile stress characteristic, and the upper interconnection includes a refractory metal having a different stress characteristic from the lower interconnection.

19. The semiconductor device of claim **15**, wherein the three-dimensional memory array includes a plurality of cell gates disposed on the semiconductor pattern and spaced apart from each other in a direction perpendicular to an upper surface of the semiconductor pattern, and

wherein each of the plurality of cell gates includes a cell gate conductive pattern including a cell interconnection, and the cell interconnection includes a tungsten material.

20. The semiconductor device of claim **19**, further comprising:
a metal interconnection over the three-dimensional memory array, wherein side surfaces of the metal interconnection have positive slopes.